COMPOST TOILETS: an option for human waste disposal at remote sites

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Compost toilets are used for sewage treatment at remote sites, however there are often problems with anaerobic conditions creating smell. The composting process is well understood, thanks to large scale composting, but the applicability of the research to small scale compost toilets is uncertain.

The heat flows and evaporative performance of a Soltran Compost Toilet at Routeburn Falls Hut on the Routeburn Track in Mount Aspiring National Park, New Zealand, were assessed. Up to 8 kg of liquid were evaporated from the evaporator during a hot day, but 2 kg of this were condensed in the compost room. This condensation reduced net evaporation, but improved the heat transfer performance of the toilet. The heat released by the condensing water exceeded the heat transferred by hot air. Overall the amount of heat transferred was small and what was transferred was quickly lost from storage by evaporation.

Separation of urine and faeces at source has been identified as the factor that could most improve composting performance in an existing toilet. Auxiliary heating improves compost performance in existing toilets, by a combination of increased rate of composting and increased evaporation of urine from the compost. Separation of urine is likely to achieve good composting without the need for auxiliary heating.

The high air flows, needed in compost toilets to ensure odours do not reach the users' nostrils, result in evaporative cooling. This ensures the compost, in existing toilet designs, will remain close to ambient temperatures; any surplus heat (biological or auxiliary) will be quickly removed by evaporation. In addition, only the recent (less than one month) additions to the compost will contribute heat. The remaining mass (one to two years of compost) contributes no heat. The conduction losses through the walls of the large container necessary

to hold this mass, eliminate the possibility of maintaining high temperatures in the pile without extremely good insulation.

However composting will initiate at temperatures above 4^0C, although the rate of composting is affected by temperature. A formula relating compost temperature, daily usage, surface area of compost, and oxygen penetration depth is proposed as a means of identifying the overload point within a compost toilet.

This research concludes that successful compost toilets can take one of two paths:

a/ high temperature (high speed) composting - to achieve this will require a small, sophisticated composting chamber.

b/ ambient temperature composting - a vault/pit composter with separation of urine. Because composting occurs at ambient temperatures, the rate of composting will vary as temperature varies. Design considerations for these toilets will need to take ambient temperature into account by sizing the surface area of the receiving chamber accordingly.

Existing compost toilet designs do not get hot, so do not fit into category (a) and have a restricted surface area, so do not fit into category (b). In many ways they are more like an ambient temperature compost toilet, but are susceptible to overloading because of the restricted surface area and addition of urine.

Composting systems occur on a continuum from the ambient temperature, adequate airflow system (double vault compost toilets) which can be likened to a 'forest floor ecosystem', to the high rate 'bacterial' dominated composting system. The design considerations for the two are totally different and one cannot be easily transferred to the other. High use sites in colder areas will need a design based on the high rate system.

Key words: Compost toilets, composting, heat transfer, evaporative cooling,

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Working in a fringe area (one associated with alternative lifestylers) can be a lonely business.

The project started in 1977 when I was first exposed to compost toilets on Stewart Island, in this respect Linda Blake and Sam Sampson must receive credit for starting the path that ended in this thesis. The establishment of the Soltran toilet at Glenorchy was due in large part to Linda's interest in alternative waste treatment systems.

While at Glenorchy many supported my, perhaps unexplainable, obsession with the toilet. In particular the Field Centre Manager, Richard Kennett but also the hut wardens over the years who have kept my backyard modifications operating, and kept the records that were used in this research. Later in the toilets history Dave Lees and Andrew Dakers installed the monitoring system which resulted in the mega-bites of data I had to process.

While doing this thesis at Lincoln many of the above people continued their support of the project in particular Andy and Dave, while some new ones were involved.

Chris Trengrove owned the pig farm I collected the pig faeces from. I am sure he never really understood why someone could be interested in such a subject, but he did get the floor of his pig pens cleaned out every couple of weeks.

Rachael carried out some microbial analysis of condensate.

Andrew Dakers my supervisor, was regularly asked questions to which there were no answers, but largely left me to get on with the job. An aspect of his supervision which possibly contributed to some of the more penetrating conclusions of this research.

My partner Chrys suffered several hours of excited and sometimes agitated discussion. A burden that was lightened for her by being half asleep in bed, requiring only a small acknowledgement that she was not yet asleep. But then, I have had to suffer similar effects from her thesis. Much of the grammatical correctness is due to Chrys's input.

DoC has been both supportive and unsupportive. On the one hand they have been tolerant of the time I spent on the toilet when I was employed at Glenorchy, and supplied the research grant. On the other hand the grape vine can be a pretty powerful deterrent to struggling toilet systems. In this respect I have heard of a cost figure circulating of $100,000. This would put anyone off a compost toilet. The sad thing is that one doesn't get a chance to respond to such rumours. After a workshop on toilets in Nelson I realise that my task is not yet complete. It is not sufficient to produce the theoretical basis for getting compost toilets operating that this thesis contains. Rather an operating system will have to be produced that matches the cost of alternatives and composts the waste with minimum to nil management input.

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GLOSSARY OF SYMBOLS

Symbol		units
α	Proportion of inlet air that is infiltration air	
A	Area	m^2
BM	Bulking material added per day	cm^3/day
BM_p	Bulking material added per person	cm^3/person
bw	Bulk weight	g/cm^3
dm	Dry matter	%
FAS	Free air space	%
g	Moisture content	kg(H_2O)/kg(dry air)
G	Water absorbed or condensed	kg/s
h	Enthalpy	kJ/kg(dry-air)
H	Height	m
J	Energy content	Joules
k	Thermal conductivity	W/m.K
Ma	Mass flow rate	kg/s
N	Number of users/carousel.day	person
P	Total pressure	kPa
P_{sw}	Saturated vapour pressure	kPa
P_v	vapour pressure	kPa
q	Rate of energy production (volume)	W/m^3
Q	Rate of energy production (total)	Watts
r	Radius	m
R	Thermal resistance	m^2.K/W
RH	Relative humidity	%
sg	Specific gravity	g/cm^3
t	Temperature	^0C
T	Absolute temperature	Kelvin
U	Heat transfer coefficient	W/m^2.K
v	Specific volume	m^3/kg(dry)
V	Volumetric flow rate	m^3/s
W	Rate of heat output	Watts

Subscripts:

$_{1...5}$	location of sensor
$_a$	Air
$_e$	Evaporation
$_c$	Conduction
$_{cs}$	Compost room sensible heat
$_{cl}$	Compost room latent heat
$_m$	Air surrounding the compost
$_p$	Compost pile
$_s$	Compost surface
$_T$	Total (ventilation + conduction)
$_v$	Ventilation

CHAPTER 1

INTRODUCTION

1.1 GENERAL INTRODUCTION

For the last 100 years, research on human faecal waste disposal has focused on cities, rather than smaller villages or remote sites. This is because the threat of epidemics affecting large numbers of people was of more concern, politically, than sick individuals in a village. In addition, cities contained an infrastructure, in the form of city councils, that:

- were responsible for public health,
- provided a concentrated funding base, and
- effectively lobbied governments to provide additional resources.

Thus the history of sewage treatment and disposal has largely been crisis driven, with new technologies arising to clean up problems that had already occurred. Large scale technologies evolved to treat the large scale problems. On-site waste treatment systems did not have this political focus, and the funding sources were isolated rather than concentrated. Research into on-site systems is now being funded, in response to rising environmental standards, cultural concerns and awareness of pollution build-up. Human faecal waste disposal is entering an era in which the limitations and cost of large scale technology (including water use), and the inappropriateness of this technology for small on-site applications, are being realised.

Some administering authorities, notably those responsible for National Parks, have localised on-site human faecal waste disposal problems. In these areas, preservation of water quality rather than wise use of water, assumes higher priority. The increasing value of clean water and recent awareness of waterborne diseases likely to affect New Zealand's clean green image have added impetus to the search for a good waste disposal system. With this focus, on-site human faecal waste treatment systems need to address the quality of discharge of all effluent, whether to ground water or surface water. With these constraints, zero discharge systems must rate highly for research. Compost toilets do not require any water and thus have the potential to be a zero discharge system.

Compost toilets were first designed in 1939 and have changed little since. Originally designed for household use they were up-sized for public sites and were seen, by managers of remote sites, as a desirable option for human faecal waste disposal. Compost toilets came to be used at difficult sites because other systems either: do not work, or are technically not feasible (lack of electricity). Thus a design which has never been optimised is being asked to operate in places where other systems fail. There has been no research that identifies the limitations of compost toilets.

Experience with an ECOS Soltran, solar composting toilet (Manufactured by: Environment Equipment (A'Asia) PTY. LTD; Australia) on the Routeburn Track, Mount Aspiring National Park, made me aware that the toilet was operating near to its limit and considerable effort went in to attempting to 'fine tune' the system. The difficulty of assessing the effect of any action and the apparent lack of improvement in compost performance stimulated my desire to research this topic. The Soltran experience invited two major questions: what is happening to all the heat that is collected in the solar room and what is needed to improve the quality of the compost? This research uses data from the Soltran to answer these questions.

The Soltran, and the heat flows through the toilet, are assessed in chapter three; while chapter four contains results of trials, carried out at Lincoln University, looking at the composting process from a small pile perspective.

1.2 OBJECTIVES

The objectives of this research were:

1/ Heat flows within the Soltran.

- To use the data collected from the Soltran to understand what is happening to the energy collected by the solar room.

- To use this understanding to recommend modifications that will: improve the evaporative performance, and improve the heat transfer to, and storage within, the compost chamber.

2/ Composting performance.

- To conduct trials in a controlled environment to establish those factors which would improve compost performance in continuous, small scale compost toilets.

- To establish areas where further work is required to develop an efficient compost toilet.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Very little research has been done that is directly applicable to compost toilets. The batch composting process is well understood (Finstein and Morris, 1975); thanks to large scale composting, however a question remains as to how applicable this research is to small compost toilet piles?

Continuous use of a compost toilet will ensure that recently added faeces will be on the surface, or very close to it. Surface effects can be ignored in a large compost pile, but emerge as vital in a small pile. In the absence of directly applicable research, the conditions at the edge of a compost pile have to be inferred from research in other fields.

With so little known about the composting process in toilets, it was difficult to narrow the field of interest.

2.2 THE EFFECT OF TEMPERATURE ON TREATMENT PROCESSES

Temperature affects the rate of reaction of all biological processes. This is incorporated into design of waste water treatment systems by use of the reaction rate constant and takes a logarithmic form (Reed *et al.*, 1988):

$$K_t = K_{20} 1.1^{(t-20)} \tag{1}$$

where K_{20} = reaction rate at 20^0C (found by experiment)

t = temperature ^{0}C (5 <t> 25)

Anaerobic processes are more affected by cold temperature than aerobic processes. This is because anaerobic digestion depends on three different groups of bacteria, each group producing the substrate for the next group. Thus, hydrolysing bacteria produce sugars and amino acids, which are used by the acetogenic bacteria to produce acetate, CO_2 and hydrogen ions. The hydrogen ions and acetate are used as a substrate by the methanogens to produce methane and CO_2 (Novaes, 1986). If hydrogen ions are not removed then the ion concentration becomes inhibitory to the hydrolysing and acetogenic bacteria, and breakdown of the waste slows considerably.

The bacteria that produce methane (methanogens), and hence remove the surplus hydrogen ions, grow very slowly at temperatures below 15^{0}C (Oremland, 1988). They will become rate limiting for the whole anaerobic process at low temperatures. Because anaerobic digestion is slow in cold temperatures, waste treatment in the cold areas of the world use aerobic ponds as a treatment mechanism (EPS, 1985).

Many remote sites are cold, and hence unsuitable for waste treatment systems that use anaerobic digestion. A septic tank, which is not heated, will be acting as little more than a sedimentation tank (EPS, 1985). Any treatment that may occur before waste water reaches receiving waters, will be occurring in the waste disposal field. If septic tanks are the only option at remote sites, a disposal field that effectively removes pollutants, will be critical to adequate treatment of sewage.

Compost toilets are also affected by temperature, but the absence of large quantities of water enable designs that allow retention of the heat from composting, within the reactor vessel. This has positive effects on the treatment process. Composting systems have the potential to be largely independent of ambient temperatures whereas water transfer systems cannot be independent of the temperature of the incoming water.

2.3 COMPOST TOILETS - GENERAL

Use of the compost process as a means of recycling organic matter and fertility back to the land has been practised for centuries. The oldest record of use of composting to recycle sewage back to the land was the Minoan civilisation (Hughes, 1980). China has supported a large population for a long time by recycling all organic waste back to farm land (King, 1939). These early compost systems involved heaps of material above ground, or material buried in a pit for a period of time (Blobaum, 1975). Other countries use double vault compost toilets. These are pit toilets with a bulking material added (Feachem *et al.*, 1983; Kalbermatten *et al.*, 1982). These early systems were mainly anaerobic composting.

Aerobic composting arose in India in 1935 when Howard developed the Indore process; named after the area where it was developed (Gotaas, 1956). This process used layers of different organic material in a heap which was turned twice in six months. The Clivus Multrum was the first of the modern aerobic compost toilets and appeared in 1939 in Sweden (Stoner, 1977). The concept has changed little since then.

There are several reports assessing the performance of compost toilets (Smith, 1981; Smith *et al.*, 1984; Stoner, 1977; Crennan, 1992a; Crennan, 1992b; Young, 1986; Enferadi, 1981). Most of the reports have identified low composting temperatures, anaerobic conditions and excess liquid build up as the main problems. One author, Crennan (1992a), noted that it was primarily public facilities that experienced problems.

Much of the published material is biased towards public facilities in remote and extreme sites for two reasons:

- compost toilets have been installed because other toilet systems are unsuitable.
- reports are commissioned, and published, by public service administrators of these areas (U.S.Army; Tasmanian National Parks; U.S.Department of Agriculture etc). Many wilderness areas have extreme climates, and are now experiencing high use requiring

innovative waste disposal options (Crennan, 1992a; Chapman, 1989).

Smith (1981) compiled a report on the performance of 33 compost toilets in National Forests in the United States, and noted that most toilets were aerobic in the top section and anaerobic in the lower section. He did microbial analysis which showed that neither bin nor continuous composting reduced faecal coliforms to acceptable levels and also found, from ash and chemical oxidation demand (COD) analysis, that composting was not complete.

Ely and Spencer (1978) found 10^4 faecal streptococci and slightly less faecal coliforms after 2 weeks, but concluded that composting is still a good method for handling waste in remote sites.

The U.S. Army commissioned a report on the applicability of compost toilets for disposal of waste from troops. This report provides a good summary of much of the data available including the Norwegian and Smith account, along with manufacturer's claims (Smith *et al.*, 1984). In a subsequent Army report (Scholze, 1985) noted:

> *there is a scarcity of technically acceptable published data regarding different aspects of composting latrines......*

Two reports assessed the performance of compost toilets in private homes. They are the Norwegian assessment of compost toilets as summarised in Leich (1981) which found large box toilets mostly unsatisfactory, while the performance of other sizes varied from good to bad. The second report was prepared by the California Department of Health and found generally poor performance especially in terms of faecal indicator species (Enferadi, 1981).

2.4 PROBLEMS OF COMPOST TOILETS

2.4.1 Temperature

Generally, continuous addition compost toilets have pile temperatures between 20^0C and 35^0C (Smith, 1981), although some lower values were recorded by Enferadi (1981). Thermophilic temperatures have only been recorded in bin composters (Leonard and Fay, 1978).

Often when compost toilets do not perform satisfactorily, cold ambient temperatures are blamed. However, it must also be remembered that the original Clivus Multrum design was to accommodate occasional use during holidays; where the gap between users allowed the recent additions at the surface to break down before new material was applied. Recent use of compost toilets is in locations with either, high use or continuous use; neither of which were contemplated in the original design (Crennan, 1992b).

Manufacturers tend to respond to problems in compost toilets by installing fans to increase airflow (Chapman, 1989; Crennan, 1992a) or, if situations permit, to install heating. Toilets with auxiliary heating have been observed to perform better than those without (Crennan, 1992a).

Without the benefit of high operating temperatures in compost toilets, there is understandable reluctance, on the part of health authorities, to approve the use of compost toilets for use in the home (they are considered a cesspool). This attitude is changing (Riggle, 1990). New Zealand authorities had the added concern of a manufacturer in Christchurch who unadvisedly used Health Department advice in publicity material (Gunn, 1991).

2.4.2 Anaerobic conditions

Anaerobic conditions produce very little heat as most of the energy in the organic matter is in the methane produced (Verougstraete *et al.*, 1985). This results in low pile temperatures, and foul smells result from sulphur being used as an electron acceptor (Oremland, 1988; Leonard and Plumley, 1979).

There have been attempts at addressing some of the problems of anaerobic conditions by various improved air flow designs (Engelder *et al.,* 1986). Many "improvements" have occurred when enthusiasts have tried various modifications (Stoner, 1977; Mother Earth News, 1983; Mother Earth News, 1984).

The addition of bulking material and regular stirring, can prevent the onset of anaerobic conditions (Smith, 1981).

2.4.3 Liquid accumulation

Generally, the airflow through the toilet evaporates liquid from the pile, and any excess is drained away as required. However, liquid accumulation is often mentioned as a problem in the literature on compost toilets (Enferadi, 1981; Stoner, 1977; Crennan, 1992b). Auxiliary heating or installation of electric fans is usually advocated as a solution, if occasional drainage is not feasible.

In some designs, notably the Clivus Multrum, liquid accumulation submerges the pile and anaerobic conditions occur, with associated odours. The Soltran was designed as a result of this problem (Ely and Spencer, 1978). It uses a separate evaporator tank to assist liquid evaporation in sites where electricity is not available (ECOS publicity data).

Disposal of greywater from other household operations (kitchen, bathroom and wash house), while not a direct problem of compost toilets, are related in the minds of health authorities who have to contend with safe disposal of both greywater and blackwater (Stoner, 1977; Enferadi, 1981). With flush systems, greywater is processed through the same equipment as human faecal wastes. Installation of a dedicated human faecal waste disposal system means a separate system must be installed for the greywater. Greywater disposal is outside the scope of this thesis.

2.5 COMPOSTING - THE PROCESS

Gotaas (1956) includes anaerobic breakdown in composting. His definition includes the requirement for reuse of the processed material:

> *In recent times, man has attempted to control and directly utilise the process for sanitary disposal and reclamation of organic waste material and this process has been termed "composting" and the final product of composting has been called "compost".*

The Chambers Twentieth century dictionary implies the requirement for reuse in its definition of compost:

> *..a mixture: a manure consisting of a mixture of decomposed organic substances.*

Composting systems can be divided into three types:

(1) dominantly anaerobic composting eg. pit toilets and primitive/poorly managed compost toilets,

(2) mesophilic composting eg. advanced/well managed compost toilets and,

(3) thermophilic composting eg. windrow composting, and large scale composting systems.

Much composting research has been done on large scale compost heaps, some of it in New Zealand (N.Z. Committee on Utilization of Organic Wastes - sixth report, 1972). The processes involved in high temperature composting are well understood (Finstein and Morris, 1975), the applicability of this research to small scale on-site compost toilets is not fully understood. There is a notable lack of scientific research into solving the problems of on-site compost toilets. In particular, the larger surface area:volume ratio of small heaps, the effect of evaporative cooling on temperatures in the surface layers, and the effect of addition of urine to the composting mass.

2.6 OPTIMISING THE PROCESS

Research into large scale composting systems often use small reactors to simulate the inside of a compost heap. The factors to be optimised to achieve rapid aerobic breakdown have been identified (Finstein and Morris, 1975). These factors are C/N ratio, moisture content, aeration, and substrate. A further factor applicable to small scale systems, and seldom alluded to in large-scale research, is retention of heat within the pile (Finstein and Morris, 1975).

In the words of Golueke (1986):

> *The compost process itself has been fairly well explored, there yet remain the uncertainties involved in relating these findings to practice, in other words, the matter of the practical versus the theoretical.*

2.6.1 C/N ratio

Carbon compounds are used by micro-organisms as an energy source as well as for structural requirements. Nitrogen is used primarily for structural requirements, therefore more carbon is required than nitrogen. The optimum C/N ratio for compost is 28:1; raw faeces are in the order of 8:1 (Gotaas, 1956).

Excess carbon (such as is found in food scraps) means nitrogen limits microbial growth and excess carbon must be removed as CO_2 before optimum conditions arise. Substrates with excess nitrogen, such as faeces and urine, volatilise nitrogen as ammonia (de Bertoldi *et al.*, 1985). This is a common odour associated with compost toilets and is well known to managers (Crennan, 1992a). Addition of urine to composting faeces will accentuate the C/N imbalance and slow the rate of composting (Shuval *et al.*, 1981). Separation of urine and faeces at source was designed into the Vietnamese double vault compost toilet (Nimpuno, 1981), and at the turn of the century some earth closet designs separated urine and faeces (Van Der Ryn, 1978).

The excess of nitrogen in faeces can be balanced, in compost toilets, by the addition of a suitable carbon source in the form of bulking material.

2.6.2 pH

Profiles of pH changes in batch composting have been drawn by Wiley *et al.* (1957) and Handreck (1990). These show a drop in pH at the start of composting; a result of acid formation from microbial oxidation of carbohydrates and sugars (Fernandes *et al.*, 1988). Later, ammonia is formed and pH rises to alkaline before slowly returning to neutrality on maturation (Handreck, 1990). Ammonia formation is sensitive to temperature and has been observed to be greater between 60^0C and 70^0C than 30^0C-50^0C (Sikora and Sowers, 1985).

Low pH of some substrates may affect initiation of composting (de Bertoldi *et al.*, 1985), but low pH seems to influence the thermophilic organisms more than the mesophilic, as compost temperature has been observed to remain below 45^0C until pH 7 is exceeded (Galler and Davey, quoted in Finstein and Morris, 1975). Jeris and Regan (1973a; 1973b; 1973c) used Warburg respirometers held at 59.6^0C with pH controlled and found the composting rate increased as pH rose from 5.6 to 7.8.

Compost toilets are based on continuous operation rather than batch operation. Schulze (1962) tried continuous composting in reactors and found that at low loading rates (9.4% fresh weight/day) pH rose to 8.0 and remained there despite the input feed being pH 6. He also found that if the feed rate was increased to 18.3% fresh weight/day, then pH dropped to acid levels (6.1). He concluded that at high loading rates, acid production exceeds acid consumption. Thermophilic temperatures were still maintained, despite the low pH, which seems to differ from the results obtained for batch composting.

Lowering of pH with high loading rates in a compost toilet could contribute to poor performance. Enferadi (1981) monitored several compost toilets and found pH to range from 5.9 - 7.9. Total coliform count appeared to decrease as pH increased. The higher pH occurred in toilets with higher temperatures and presumably, higher microbial activity. All toilets were fitted in private homes.

Acidic pH at lower temperatures favours fungal growth (Jeris and Regan, 1973c). A possible cause of the compost not moving down the chamber of Clivus Multrums, could be dense fungal hyphae in compost with low pH.

pH of some commonly composted materials are:

	pH	Reference
Night soil	7-9	Shuval *et al.* (1981)
Sewage Sludge	7.5	McKinley *et al.* (1985b)
Pig faeces	7.5	Schuchardt (1985)
Refuse (MSW)	6	Jeris and Regan (1973b)
Garden heap	6	Handreck (1990)

2.6.3 Bulking material

Haug (1986a; 1986b) noted that bulking material has two roles in a compost pile; energy amendment (usable carbon) and optimising aeration/moisture levels.

Most bulking materials are organic in origin, and thus will fill both energy and aeration requirements, but the energy source must be available to micro-organisms. Availability has two aspects, it must be easily degradable and it must be well distributed. Easily degradable sources are sugars and carbohydrates, least available is lignin (Golueke, 1992). It is desirable to distribute bulking material evenly through the pile, as organic carbon is not volatile at composting temperatures. Redistribution to areas short of carbon cannot occur by vapour movement (this is possible with nitrogen as ammonia). This redistribution problem is unique to solid systems, as with liquid based systems soluble carbon will move by mixing/diffusional processes (Golueke, 1981). To achieve an even distribution, bulking material should preferably be finely divided.

Dry bulking material is able to provide structural support and absorb surplus moisture from the faeces. Faeces have a high moisture content and the final mixture must have a moisture content within the composting range (40%-70% see section 2.6.4). Addition of dry bulking material can be used to achieve such moisture contents.

Materials that have been used as bulking material include:

- wood (shavings, sawdust, and wood chips),
- leaves,
- bark,
- municipal solid waste (paper, kitchen scraps),
- straw,
- rice hulls,
- grape marc,
- water hyacinth,
- shredded rubber tyres,
- recycled compost.

Sawdust/shavings are commonly used bulking materials in compost toilets, being a by-product of the timber milling industry and easy to handle. However sawdust is composed mostly of lignin and as such its degradation is slow and generally carried out by fungi which do not survive well at high temperatures (Frankos *et al.*, 1982). Thus sawdust/shavings do not provide additional energy.

Other tree products that have been used include "Green" wood (small branches, hedge trimmings, saplings). These have not yet lignified their fibres and have a good supply of wood-sugars. They are a good source of energy for microbial breakdown (Golueke, 1986).

Leaves have a very high C/N ratio and seem a good source of bulking agent, but they have a surface that is resistant to microbial attack (Golueke, 1992). Crushing leaves breaks the surface and makes the nutrients more available.

Bark can be composted by itself and would be suitable as a bulking agent. It is roughly 1/3 lignin, 1/3 cellulose, 1/3 reducing sugars. Self-heating trials did not get pile temperature into the thermophilic range (Campbell *et al.*, 1990a; 1990b). Similarly, Bagstam and Swensson (1976) found additional nutrients were required to compost spruce-bark at high temperatures.

Newspaper has been found to be less degradable than other paper as the mechanical kraft process leaves the cellulose fibres surrounded by lignin. The lignin restricts access to the more easily digestible cellulose fibres (Golueke, 1992).

Municipal solid waste (MSW) includes a high proportion of organic scraps from the kitchen. These can be used as bulking material and provide organic carbon to balance the high nitrogen content of faeces (Stoner, 1977).

Straw has a good supply of soluble carbohydrates. These are readily available and give rise to a faster temperature rise, and more sustained temperatures throughout than sawdust (Hay *et al.*; 1988a; 1988b; de Bertoldi *et al.*, 1980).

Grape marc has been successfully composted, but has a low pH (Inbar *et al.*, 1988).

Water hyacinth, a problem weed, was added to nightsoil and composted in Thailand. This was seen as controlling a problem and supplying nutrients to the land (Polprasert *et al.*, 1980).

Some bulking materials provide only structural support to a composting pile i.e. they are added to maintain a network of large and small pores that will optimise the movement of oxygen into a pile. Chips made from rubber tyres and recycled compost are a structural addition for aeration. Wood chips, sawdust etc, will be primarily structural as lignin is not easily available.

2.6.4 Moisture content

Microbial processes can only operate in an aqueous medium and micro-organisms use substrate that are dissolved in water (Jimenez and Garcia, 1989). For successful composting, moisture content should be in the range of 40-60% wet mass (Gotaas, 1956), although Jeris and Regan (1973b), working with municipal solid waste (MSW), found optimum moisture content to be 70%. The upper limit occurs because the larger pores become anaerobic, while the lower limit is where the lack of water in the small pores reduces micro-organism mobility, and diffusion of solutes (Miller, 1989). Raw faeces have a moisture content of around 80% and so will be mostly anaerobic within a few millimetres of the edge. Addition of dry bulking material will absorb some of the moisture and reduce moisture content (Haug, 1980).

2.6.4.1 Humidity within a compost pile

Rothbaum and Dye (1964) found that bacteria multiplied when humidity rose above 95% in wool. Humidity has been noted as important for the germination of spores on leaves

(Juniper, 1990). Composting relies on surface acting micro-organisms, therefore it is likely that composting is affected by the humidity of the air in the pile.

In an enclosed environment, an equilibrium develops between the humidity of the air and the moisture of the material. This is termed the "equilibrium moisture content" or EMC. It is a concept that is mostly applied to drying of serial grains, and several equations have been used to calculate it (Brooker *et al.,* 1974). The Chung and Henderson equations have been used to establish the EMC of pine shavings and poultry manure; and these equations can be applied to composting (Flood *et al.,* 1987). Using Flood *et al.*'s constants in the Chung equation for the moisture content range of composting gives:

Moisture content %	RH %
40	99.85
50	99.98
60	100

Hence for the moisture contents that occur in compost the air will be saturated. Unsaturated air surrounding the compost may dry out the edge of the pile and adversely affect microbial activity. This edge effect is not considered in large scale systems, but is important in compost toilets where continuous addition to the surface of the pile means much of the early breakdown occurs in this zone. This aspect has not been researched.

2.6.4.2 Pore water in a compost heap (the pore water/air interface)

As bacteria can only operate in an aqueous environment, water in pores becomes important to allow optimum conditions for bacterial growth.

Moisture content determines the size of pore that will be filled with water (Miller, 1989). As the moisture content gets above 60%, the pore size filled increases rapidly (figure 2.1). This coincides with the upper limit of moisture content noted for composting. Oxygen diffusion through water is 10,000 times slower than diffusion through a gas (compare 2.56 x 10^{-5} cm^2/sec for water with 0.189 cm^2/sec for a gas-filled space (Miller, 1989)).

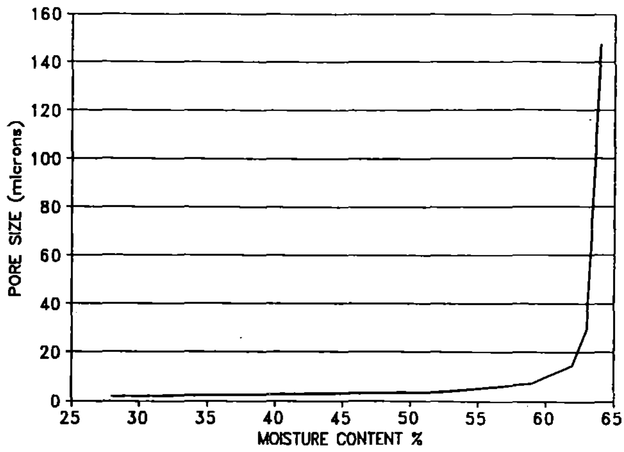


Figure 2.1 The influence of moisture content on pore size filled with water.

It is the lack of oxygen, which is the result of slow diffusion in water, in conjunction with the large pores being filled with water, that determines the upper moisture limit for composting.

A prerequisite to optimising growth conditions, and maximising heat output is a pore size distribution that has both good aeration through macro-pores and adequate sites for bacterial activity in smaller pores. The role of mixing (faeces and bulking material) to achieve this should not be underestimated.

2.7 <u>AERATION</u>

All current compost toilet designs have air surrounding all, or part of the pile. This air must contain adequate oxygen to sustain biological oxidation. Excess air flow however, increases the evaporation rate, preventing high pile temperatures, and affects the micro-organisms at the edge of the pile.

2.7.1 Movement of air within the pile

Factors that affect the movement of air within the compost pile are: mixing, total pore space (porosity) and the amount of water in the pores (free air space).

Mixing is done by toilet managers, with mechanisms that vary between designs. The frequency of mixing is thus greatly influenced by the diligence of the operator; some poorly managed ones have no mixing. As mixing cannot be relied on as a means of aerating the compost pile, movement of oxygen into a pile by diffusion is important.

Free air space is a concept that has been borrowed from soil science, to help quantify the amount of air filled voids required for optimum composting. It is derived from porosity, but differs from it in that porosity is a measure of void space, be they full of water or air, whereas free air space represents voids that are air filled only. Free air space will change as moisture content changes, whereas porosity will not (Schulze, 1962).

Schulze derived free air space for compost:

$$FAS(\%) = (1 - \frac{bw*dm}{sg})*dm$$

Where:	bw	= bulk weight	g/cm^3
	dm	= dry matter	%
	sg	= specific gravity	g/cm^3

Optimum FAS values lie between 30% - 40%. Haug (1980) considered the minimum to be 30%, but notes that the value will rise as composting proceeds due to moisture removal. Inbar *et al.* (1988) composted cattle manure and grape marc with FAS of 65% and 50% respectively (calculated from volumetric water content of 28% and 35%). Jeris and Regan (1973b) found that the optimum moisture content was higher for paper than for beef feed lot straw (65% as against 53%), but the free air space was relatively constant at 32%-36%. Carmichael *et al.* (1989) devised a sampling vessel to overcome the difficulty in obtaining an undisturbed sample, for measuring FAS in the field. FAS ranged from 14% to 54%, and their results showed that as FAS increased the pile warmed up faster. Thostrup (1985) considered free air space: "*...the most important and the most difficult factor in composting processes*".

2.7.2 Size of particle

Measurement of free air space does not differentiate between large and small pores, so it does not help in calculating the optimum size of bulking material. Large heaps with forced aeration have a requirement for many large channels to move air through the compost mass with a minimum of short circuiting. Larger particles are used for bulking material (wood chips 12-20 mm in size (Frankos *et al.,* 1982)), or the heap is turned.

Toilets on the other hand have only short distances that oxygen must penetrate. With low use of the toilet this material will be buried only a few centimetres before breakdown is complete. The maximum distance that oxygen will have to penetrate in any compost toilet design, is about 600 mm i.e. the middle of a 1.2 m container. In large heaps oxygen levels reach 0% to 2%, 600 mm in from the edge (Carmichael *et al.*, 1989). Or to put it another way, the maximum distance a composting particle may be buried in a compost toilet, is similar to the maximum distance of the cool outer layer of a large scale compost heap.

With depth of burial influencing the supply of oxygen to a compost toilet pile, composting in the surface layer would be improved, if a greater proportion of fine particles was used. This would maximise the organic breakdown before deep burial restricted oxygen diffusion to the composting mass. Poincelot (1974) noted that grinding increased the composting rate (increased surface area), and Golueke (1981) felt particle size was of paramount importance among the physical characteristics of compost. Smaller particle sizes increase the surface area available to attack, and increase the rate of composting. De Bertoldi *et al.* (1985) noted the...

> *Surface area:volume ratio of the particles has a direct influence on the manner and speed of degradation.....*

There will be a particle size, below which, the bulking material particles will not adequately fill their other role of allowing air to diffuse into the pile. However air diffusion into the pile may well be less important than the speed of the composting process in the surface layer of a compost toilet pile. Edge effects, including: the air surrounding the pile, the movement of oxygen into the pile, and the rate of composting, are crucial for compost toilets but largely insignificant in large scale composting.

Controlling air flow to limit the effect of evaporative cooling conflicts with the ability to use the toilet on a regular basis; as air exchange occurs when the toilet seat is lifted.

2.8 ACHIEVING A WARM PILE

Temperature has a greater effect on the composting process than any other factor (McKinley *et al.*, 1985a; 1985b). A compost toilet that gets hot, will retain heat in the pile by addressing both sides of the energy balance: heat production and heat loss. Pile temperature will rise until heat production = heat loss.

2.8.1 Heat production

Faeces will supply the bulk of the energy and nutrients for the composting process. Lentner (1981) noted that human faeces have an energy content of 21.5 MJ/kg(dry). Of this, 38% (46% of volatile solids) will be degraded in the composting process (Haug and Ellsworth, 1991), thus some 7.7 MJ/kg(dry) will be released in the composting process. This energy may be supplemented by using bulking material of adequate degradability (Haug, 1986a).

Composting is a biochemical reaction and the rate of the reaction is temperature dependent. That is, heat produced from a compost pile is dependent on the temperature of the pile while the temperature of the pile is in turn dependent on the heat production (MacGregor *et al.*, 1981). A rise in pile temperature will only occur if heat production exceeds heat loss.

In batch composting, two heat output peaks occur, the first at 40^0C the second at 60^0C. The first represents the optimum temperature of mesophilic micro-organisms while the second represents the optimum temperature of thermophilic micro-organisms. The drop in heat output between the two peaks is due to conditions that are too hot for mesophilic micro-organisms and not warm enough for thermophilic micro-organisms (Viel *et al.*, 1987). In fact there are two overlapping curves, one for mesophiles and one for thermophiles. Inbar *et al.* (1988) noted a third peak in the heat output curve, at 22^{0}C. They put the other two peaks at 35^{0}C-40^{0}C, and 55^{0}C.

Several workers have measured heat output rates. Maximum rates have been measured by Mote and Griffis (1982) as follows:

27 W/kg(dw)	cow manure
28 W/kg(dw)	cotton gin trash
20 W/kg(dw)	cotton gin trash

They also summarised other published values:

19 W/kg(dw)	municipal waste (21.2 W/kg(volatile solids)
12.5 W/kg(dw)	oat straw
5 W/kg(dw)	wool

Viel *et al.* (1987) working with sewage sludge found maximum power of:

14 W/kg(dw)

These heat output maxima, correspond to peaks noted for oxygen consumption (Fernandes *et al.*, 1988).

Restricting airflow will reduce heat output as oxygen will become limiting to growth. This situation can occur unintentionally in a toilet pile when air is excluded from the mass by either: compaction and elimination of porosity, or excess water filling the pores, resulting in anaerobic conditions. The low temperatures found in pit toilets, and simpler compost toilets, have been attributed to anaerobic conditions (Shuval *et al.*, 1981).

A temperature/heat output curve of microbial origin will have an upper temperature limit beyond which heat induced microbial inhibition exceeds the benefits of increasing temperature (Edwards, 1990). A large pile can be cooled by forced aeration with evaporative cooling to ensure that the microbial activity is not impaired (MacGregor *et al.*, 1981; Sikora and Sowers, 1985). In these large piles it was felt that 60^0C is the upper limit beyond which significant impact on biological activity is noted (MacGregor *et al.*, 1981). Work by McKinley *et al.* (1985b) found optimum values to be lower (55^0C-60^0C).

The maximum activity per gram of compost occurs in the mesophilic temperature range, at 35^0C-45^0C (McKinley *et al.*, 1985b). Campbell and Darbyshire (1990b) working with tree bark found the greatest decomposition (most CO_2 produced) in reactors held at 40^0C. This evidence suggests that failure to achieve thermophilic temperatures in compost toilets will not impair the process of stabilisation of the waste, but temperatures in the high 30's will have to be obtained.

To achieve high temperatures in a composting pile requires both high heat output rates and retention of this heat in the pile. This is easy to achieve with batch composting systems such as the bin composter (Leonard and Fay, 1978), but is more difficult with continuous systems. That is, only the recently added material will have enough residual sugars and carbohydrates to be able to breakdown rapidly and contribute large quantities of heat. The remainder of the compost will produce very little heat, as all of the sugars and carbohydrates are used and the more refractory organics such as lignin will be slowly breaking down.

Thus for small, continuous addition piles, such as compost toilets, excess pile temperature that impairs microbial activity, is not likely to be a problem. Retaining the heat produced within the pile is a problem.

2.8.2 Heat loss

Heat can be lost from a pile in two ways, conduction and ventilation. In large compost heaps with forced aeration, ventilation losses dominate; Finstein *et al.* (1986) found that 98% of the energy was lost by evaporative cooling (conduction losses were 2% of the total)

Small heaps have a bigger surface area: volume ratio and the amount of heat lost by conduction becomes significant. Viel *et al.* (1987) found that three-quarters of the heat produced in his reactors was lost by conduction through the walls of the reactor. Thus for small piles (compost toilets), loss of heat by conduction becomes very significant.

2.8.2.1 Conduction losses

Conduction losses are minimised by increasing the insulation surrounding the pile. For large heaps no insulation is required as compost itself is a reasonable insulator (Poincelot, 1974; Gotaas, 1956; Haug, 1979). Tollner and Verma (1987) measured the conductivity of organic potting mix composed of pine bark (similar insulation value to compost) at about 0.2 W/m.K. This is about the same as low density brick or dense timber. Considerable variation was noted with different moisture contents.

Heat loss by conduction has two components: conductivity of the insulation material and the surface area of the vessel. Compost toilets, being an accumulation tank holding 1-2 years of compost, will have a large surface area compared to the small volume of compost that is rapidly breaking down (2-3 weeks of contributions). The total energy being produced will be low and the surface area of the insulation will be large. To maintain a large temperature difference between the compost in the tank and the outside air will require very efficient insulation or a smaller tank.

2.8.2.2 Ventilation losses - evaporative cooling

Ventilation losses have two components; heating of the dry air and evaporation of water vapour. MacGregor *et al.* (1981) found that 90% of the energy was removed by vaporisation of water, and only 10% in heating the air. Warm moist air holds large quantities of energy and when this air leaves a compost heap the energy is removed. This effect is termed evaporative cooling and is used to keep pile temperatures below those that are likely to affect microbial activity (Sikora and Sowers, 1985). It can also be used to dry the compost (Haug, 1986b).

The energy contained in air, as warm air and water vapour, is termed enthalpy (ASHRAE, 1989). Water vapour will move from a region of high enthalpy to a region of low enthalpy, thus enthalpy difference provides the driving force for energy that is being removed by water vapour movement and hot air.

While conduction losses are linear in relation to temperature difference, energy losses due to vapour movement increase exponentially with temperature (see figure 2.2). Vapour movement is therefore potentially a much more significant source of energy loss at high temperatures.

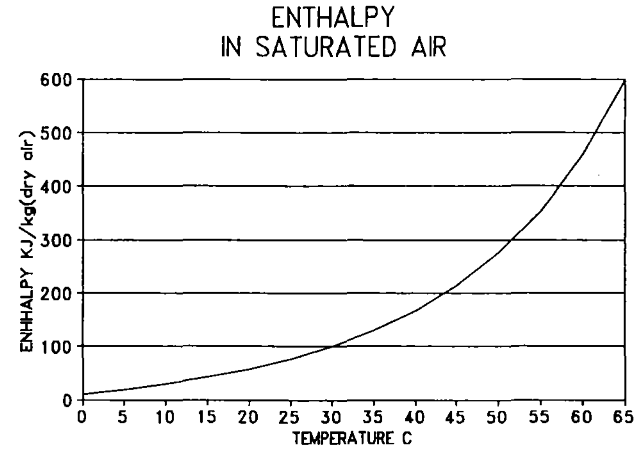


Figure 2.2

The rate of diffusion of oxygen and water vapour are similar (Incropera and DeWitt, 1985). If no heat were produced in a compost pile, water vapour would move outwards at approximately the rate of oxygen diffusion inwards. However as the compost pile heats, water vapour movement out of the pile increases, whereas oxygen diffusion decreases with higher temperatures. Thus the potential for heat loss (from evaporative cooling), is greater than the potential for heat production (from oxygen diffusion) in a pile where there is no limit on vapour movement.

It is impossible to have thermophilic composting based on oxygen diffusion without providing a vapour barrier to prevent the loss of heat by evaporative cooling.

In a large compost heap the outer layer provides the vapour barrier. In small scale systems at laboratory scale the vapour barrier is achieved by enclosing the compost in an impervious container and restricting air flow (Fernandes *et al.,* 1988). Compost toilets resemble laboratory scale, rather than large scale systems, therefore an impervious container and restricted air flow will be essential to achieve high temperature breakdown.

2.9 SUBSTRATE-QUANTITIES

Gotaas (1956) listed data for humans (table 2.1):

	FAECES	URINE
QUANTITY per day - wet	135-270 gms	1.0-1.3 litres
QUANTITY per day - dry	35-70 gms	50-70 gms
Moisture content	66-80%	93-96%

Table 2.1 Daily quantities of faeces and urine - source: Gotaas (1956).

Considerable variation in weight and consistency occurs between individuals, their diets and their culture. Feachem *et al.* (1983) collated measurements from around the world and concluded:

Individual wet faecal weights vary from under 20 grams per day to 1.5 *kilograms per day. When national or regional averages are considered, however, Europeans and North Americans produce daily between 100 and 200 grams, whereas people in developing countries have average daily wet faecal weights of 130-520 grams. Vegetarians generally have higher faecal weights than other groups, and faecal weights in rural areas are higher than in towns.*

A New Zealand study into breakdown of human stools in soils, documented differences in breakdown rates between vegan, vegetarian and omnivore diets, and compared these with carnivores (dogs). The differences were attributed to fibre content (Jenkins, 1990).

2.9.1 Composition of substrate

Faeces are a mixture of food that hasn't been digested, body waste products such as bile from the liver and a part of the intestinal flora; 70%-86% is water (Lentner, 1981). The mixture is 14%-30% bacteria, and 25%-40% food residues (Jenkins, 1990). The food residues are mostly indigestible cellulose and hemicellulose as simple sugars are not excreted by healthy adults (Lentner, 1981).

Comparing human faeces with other materials (Gotaas, 1956):

	Composition on dry basis %					
	Organic	Mineral	Nitrogen	Phosphate	Potash	C/N
Faeces	88-97	3-12	5.0-7.0	3.0-5.4	1.0-2.5	6-10
Fresh sewage	60-85	15-40	5-10	2.5-4.5	3.0-4.5	
Primary - digested	35-60	40-65	1.0-3.5	1.2-4.0	0.1-0.5	6
Municipal Solid Waste	71.5	28.5	1.07	1.16	0.83	34
Pig			3.75	3.13	2.5	

Table 2.2 Comparison of human faeces with other materials - source: Gotaas (1956).

Much of the composting research has been carried out using sewage sludge. Sludge is slightly lower in most macro nutrients because of the higher mineral content (grit), while MSW is comparable to sludge but with a much higher C/N ratio. Faeces composted as fast as sludge (Snell quoted in Shuval *et al.* (1981)), despite a proportion of the sludge solids having their origin from washing water solids, kitchen scraps etc.

Pig faeces have a nutrient content similar to human faeces and, as a pigs digestive system is more comparable to a humans than ruminants are, it was felt that pig faeces could be used as an adequate substitute for human faeces for this research.

2.10 MICROBIOLOGY OF COMPOSTING

All compostable raw materials have a substantial content of resident microorganisms, usually on the surfaces of the material. In sewage sludge, Nakasaki *et al.* (1985b) found 3.6×10^7 bacteria, $<10^3$ actinomycetes and 4.2×10^2 fungi per gram dry mass. Jenkins (1990) looked at human stools and found bacteria accounted for over 20% of the stool's dry mass. This amounted to 12×10^{10} bacteria per gram of fresh faeces. Municipal solid waste is known to contain around 2.3×10^8 coliform and 3.9×10^4 faecal coliforms (Finstein and Morris, 1975).

Of the bacteria, several species exist that are advantageous to the breakdown of organic matter. Jenkins (1990) quoted Wedekind *et al.* who reported 1.2×10^8 cellulolytic and 1.8×10^{10} hemicellulolytic bacteria per gram faeces.

Much of the nitrogen in faeces (50%) is tied up in bacteria (Jenkins, 1990), and as dead microbial cells are readily metabolised, the conditions are right for a rapid breakdown of the material.

Composting is a very complex microbial ecosystem. There will be many species contributing to the composting process, and there will be beneficial associations as well as disadvantageous competitive ones. Golueke (1992) noted several syntropic interactions in compost; that is where one group of organisms produces the substrate for another. In particular, acidifying bacteria early in the process produce acids (acetic, butyric etc) that then become a food source for a different group of bacteria.

2.10.1 The mesophilic stage

Readily available substrate are used first and as a result organic acids are formed and the pH drops. The rise in temperature is initially beneficial as biochemical reactions are able to speed up. Temperature, pH, and substrate changes are rapid but the microbial community adapts to the new conditions (McKinley *et al.*, 1985b). However stability within the mesophilic community is not achieved.

Temperature rises beyond the optimum for mesophilic organisms and any further rise decreases the activity of the mesophilic organisms. No group of micro-organisms can be singled out as being most important.

2.10.2 The thermophilic stage

The thermophilic micro-organisms are completely different from the mesophilic micro-organisms. It is dominated by bacteria (Gaby *et al.*, 1972). The rate of heat output increases to a new maximum; higher than the maximum in the mesophilic stage.

Thermophilic micro-organisms are adapted to survive in environments hotter than 45^0C. Biochemical reactions occur faster and hence more heat is produced, but there is some evidence that thermophilic micro-organisms have less microbial activity per gram of compost than their mesophilic counterparts (McKinley *et al.*, 1985b). It has been noted that high temperatures do not occur until pH rises above 7.0, indicating that thermophilic micro-organisms are sensitive to low pH, (Galler and Davey quoted in Finstein and Morris, 1975).

Mesophilic bacteria have been isolated from a thermophilic compost heap (Nakasaki *et al.*, 1985c). It appears they are able to survive but contribute little to the respiratory activity of the whole. The ability of some pathogens to survive at temperatures up to 100^{0}C has been noted (de Bertoldi *et al.*, 1988).

2.10.3 Batch versus continuous composting

The magnitude and speed of temperature changes in batch composting systems do not allow formation of a stable microbial community. Rather the community undergoes microbe-temperature interactions through the mesophilic and into the thermophilic stage (Finstein and Morris, 1975).

Continuous systems, on the other hand, will have smaller temperature changes and micro-organisms will be able to adapt to the operating temperature (Finstein and Morris, 1975). Any new material will be quickly heated and its microbial population infused with micro-organisms from the surrounding mass, eliminating the need for microbial progression.

2.10.4 Pathogens

Composting is accepted as a "process to further reduce pathogens" by the USEPA (U.S.Environmental Protection Agency, 1980). The compost must be held above 55^{0}C for 3 days. The mechanisms causing elimination of pathogens from compost are:

- substrate depletion,
- antibiotics produced by other organisms (antagonism),
- competition,
- temperature,
- time.

Substrate depletion occurs because the pathogens, which are adapted to use body tissues and readily assimilable organic matter, find their supply of nutrients depleted by other organisms feeding on the same food source (Golueke, 1982).

Antibiotic effects on pathogen removal have been demonstrated by Wiley (1962). He considered antibiotic effects to be of equal importance to thermal kill. He found that Salmonella paratyphus-B, and S. cairo, death rates in compost were much faster than death rates for organisms held at the same temperature in bouillon culture (2 days v 8 days @ 50^0C). Gaby *et al.* (1972) composting solid waste could not isolate any "*water-soluble or lipid-soluble materials, which were antagonistic (antibiotic) for Gram-negative or Gram-positive bacteria*" from the compost at any time during the process.

Competition arises when pathogens find themselves in a modified environment, not only do they have to use new food supplies but they also have to compete with an indigenous population that is already adapted to the environment (Golueke, 1982). In addition most pathogens are facultative anaerobes and would need to compete in an aerobic environment (de Bertoldi *et al.*, 1988).

Temperature effects are generally credited with most pathogen destruction in compost. The thermal death times of pathogenic organisms have been well described by Feachem *et al.* (1983) - See figure 2.3.

Feachem was aiming to identify a safety zone within the time-temperature continuum, and trials support the broad thrust of the figure. For example Wiley and Westerberg (1969) found the thermal death time of poliovirus type 1 at 60^0C was 5 minutes, Feachem's figure indicates for all enteric viruses a time of 2 hrs. On the other hand Wiley found a thermal death time for Ascaris lumbricoides at 60^0C of 60 minutes. Feachem's graph indicates a time of 30 minutes.

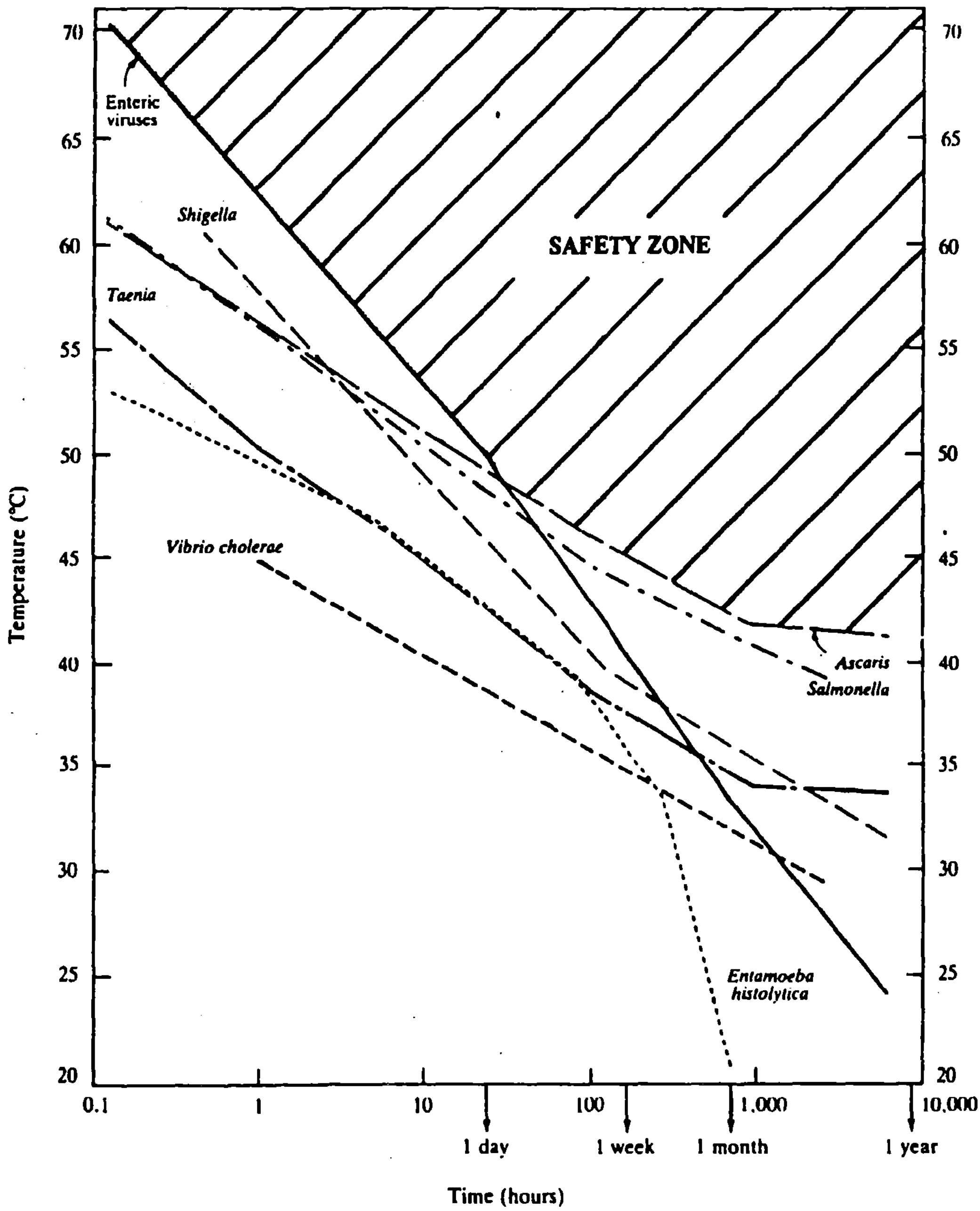


Figure 2.3 The effect of temperature on pathogen death rates in compost. Source: Feachem *et al.* (1983)

Shuval *et al.* (1981) produced a graph of destruction of Salmonellae, faecal coliforms and total coliforms which was far from linear for the first few days. Cooper and Golueke (1979) working with coliforms, faecal coliforms, and faecal streptococci found an initial growth phase followed by decline.

Gaby *et al.* (1972) found Salmonella typhurium inserted into windrows at $49^{0}C$ dropped from 10^{8} cells/ml to less than 10^{2} cells/ml after 20 days. She could not detect faecal coliforms after 2 weeks of composting.

Feachem's figure indicates that, at the operating temperature of a compost toilet, a holding time in excess of one year would be required. Time is one factor that is readily available in a compost toilet.

On the other hand, Cooper and Golueke (1979) took samples from the hot and cold sections of the compost pile and found that the number of coliforms and faecal coliforms remaining were very similar for the two different temperature zones. This suggests that mesophilic composting may be as effective as thermophilic composting at pathogen reduction.

2.10.4.1 Efficacy of mesophilic composting

Cooper and Golueke (1979) found in their study of faecal streptococci death rates that the low temperature zones of the pile had a similar death rate to the high temperature zones. Combining this result, with Wiley's (1962) claim of the importance of antibiotic effects, suggests that temperature may not be the overriding determinant of pathogen elimination. If this is so, then a compost toilet design that operates at mesophilic temperatures, with a long holding time, may be as effective at pathogen control as a short time at thermophilic temperatures.

Pathogen elimination at mesophilic temperatures must be inferred from the literature as most pathogen reduction trials have been done in large piles with high temperatures.

Inferadi (1981) claimed "*The inability of the mesophilic system to eliminate pathogens is well documented*". She claims that Reeves' (1959) paper supports her thesis. Curiously

Reeves' paper contains some evidence to support the contrary view i.e. that mesophilic temperatures do destroy pathogens. In his paper, when total bacteria were high, coliform bacteria were low, and vice versa except for the 600 mm depth when both total and coliform bacteria were low (see Reeves, 1959; table 3 page 562). High total bacteria counts (low coliform) occurred at 50mm and 100mm in from the surface. Temperatures were not measured, but this close to the surface they would almost certainly have been in the mesophilic range.

It is tempting to take the data from various compost toilets around the world to support the lack of pathogen destruction at mesophilic temperatures (Enferadi, 1981). However all the toilets monitored in the data have both urine and faeces entering the compost chamber (none indicate the contrary). Cooper and Golueke (1979) showed that leachate is good at moving pathogens through compost. Therefore it is possible that mature compost at the bottom of the pile, will be continuously reinfected with pathogens carried through the pile in the leachate from the faeces and urine added to the surface. If this is the case, then mesophilic composting may be more effective than it appears from Enferadi's data. The possible effectiveness of mesophilic composting is also indicated by Enferadi's data when she noted that toilets with warmer temperatures (25^0C-33^0C i.e closer to mesophilic optimum temperatures), contained fewer indicator organisms.

Other evidence to support the effectiveness of mesophilic composting can be seen in the literature on salmonella. Burge *et al.* (1987) reported that composts supported the regrowth of salmonellae, but Millner *et al.* (1987), found suppression of salmonellae regrowth if the compost was cured at mesophilic temperatures.

Microbial activity is maximised at upper mesophilic temperatures (McKinley *et al.*, 1985b) and competition and substrate depletion are two factors working to eliminate pathogens from compost. This suggests that a toilet design that operated close to mesophilic optimum temperatures (35^0C-40^0C), with separation of urine (eliminating transfer by leachate), would be effective at eliminating pathogens, if reasonable time is allowed.

2.11 COMPOST TOILETS - A FOREST FLOOR ECOSYSTEM

The microbiology of high rate composting as described above is dominated by bacteria, actinomycetes and fungi (Finstein and Morris, 1975). With the high temperatures involved, and the speed of the composting process there is little chance for higher organisms to become established. Compost toilets on the other hand operate over long periods of time at low temperatures. The establishment of a microflora that includes protozoa and higher organisms is possible. Indeed manufacturers' claims of 'seeding' a new toilet, with peat or recycled compost, suggests a complex ecosystem being involved, yet this research has found no references in the scientific literature to the contribution of higher organisms in compost toilets (see: Smith, 1981; Smith *et al.,* 1984; Stoner, 1977; Crennan, 1992a; Crennan, 1992b; Young, 1986; Enferadi, 1981). Omission from the literature would suggest their contribution is not important, but a similar ecosystem, the breakdown of faeces on soil, notes: *"there is no other example of a similar habitat where so many organisms in such large numbers act simultaneously in the processes of biological decomposition"* (Lodha,1974). Included in Lodha's 'many organisms' were: *"....Bacteria, Actinomycetes, Myxobacteria, fungi, Protozoa, molluscs and nematodes"*. Stout (1974) noted the catalytic effect of protozoa on microbial metabolism. It was felt that protozoa predated on the bacteria and accelerated the rate of turnover of nutrients. The role of higher organisms is also acknowledged in effluent disposal fields (Bernhart, 1973).

In both decomposition of dung and effluent disposal fields, the higher organisms play an important role. Is that role any less in a compost toilet? It is possible that higher organisms (protozoa etc) maintain the permeability of the compost, as they do in an effluent disposal bed (Bernhart, 1973). Their contribution, to successful composting, may be greater than their consumption of organic matter. Curiously this fact is often acknowledged in literature on garden compost heaps (Martin, 1992).

Viewing a compost toilet as a 'forest floor ecosystem' may not be scientifically correct but it does help to understand why compost toilets are sensitive to good management and why they are easily overloaded.

2.12 SUMMARY

The composting process is well understood, due to large scale composting being used as a means of coping with large volumes of sewage sludge and municipal solid waste. What has not been researched is the applicability of this knowledge to small piles and in particular to compost toilets.

Edge effects and heat losses by evaporative cooling are two aspects that dominate in small piles but can be ignored in large piles.

Very little research has been done on continuous systems. They differ from batch systems in that, all stages of decomposition occur simultaneously (from fresh to exhausted). Hence they will have a lower energy density (J/kg) than batch systems. Compost toilets are a continuous system, hence a lower energy density must be added to the characteristics of a small pile.

A hot compost pile is desirable. If we are to achieve this within a compost toilet we must first understand the nature of heat production and heat loss from small piles. If it is not possible to achieve a hot pile, especially in toilets with low use, then we need to know the efficacy of mesophilic digestion. Very little research has been done on pathogen reduction at mesophilic temperatures.

CHAPTER 3

ANALYSIS OF THE "SOLTRAN" DATA

3.0 INTRODUCTION

A two unit Soltran compost toilet was built at Falls Hut on the Routeburn Track, Mount Aspiring National Park, in December 1985. It was installed as an experimental toilet, because of the concern that overseas tourists may introduce waterborne disease to National Parks. Funding was from the Tourist and Publicity Department.

The hut accommodates around 5000 bed-nights over a 200 day tramping season, mostly confined to the summer months. The toilet produces 800-850 kg of compost per year (155-164 gms/bed-night). Staff based at the hut maintain the toilet. They also keep a diary of: hut usage, compost temperatures, liquid levels and weather observations. This has provided useful background for the current research.

Some months after it had been opened, it was apparent that compost temperatures were not as high as manufacturer's claims had led us to expect. In addition the evaporator tanks had to be drained of urine, on two occasions in the first year. Different types and combinations of bulking material were tried and found to have little effect on compost temperatures, and compost quality. It was noted that chambers started in January and February produced better compost than those started in November. This suggested ambient temperature had more effect than bulking material regimes.

Investigations then focused on the disparity between the size of the solar collector and the measured temperature rise in the compost room. Heat collected in the solar room was not being transferred to the compost room. Additional solar heating, using water filled solar panels, was installed in one chamber to augment the air transfer system of the original design. This gave higher temperatures in the liquid of the heated chamber, but the heat was quickly lost from storage. The net effect was a 7^{0}C difference in mean liquid storage temperature, but only a 1-2^{0}C difference in mean compost temperature. There was no detectable difference in compost quality between the two units.

We were generally happy with the quality of the compost produced. Emptying the toilet was *not* an onerous task, but it did seem that the sun's energy was not being efficiently used to evaporate the liquid and heat the compost.

Photo 3.1 The Soltran compost toilet (lower left) with falls hut behind. Note the alpine area beyond the hut.

In January 1989, the Department of Natural Resources Engineering (DNRE) at Lincoln University installed ten AD590 temperature sensors and three humidity transducers (Automation engineering humidity transducer 15-840-01) throughout the air flow system of the toilet. This was supplemented later with measurement of solar radiation. The data from these sensors was automatically collected on a half-hourly basis by a Campbell CR10 data logger and down-loaded to cassette tape. The location of the sensors is shown in figure 3.1.

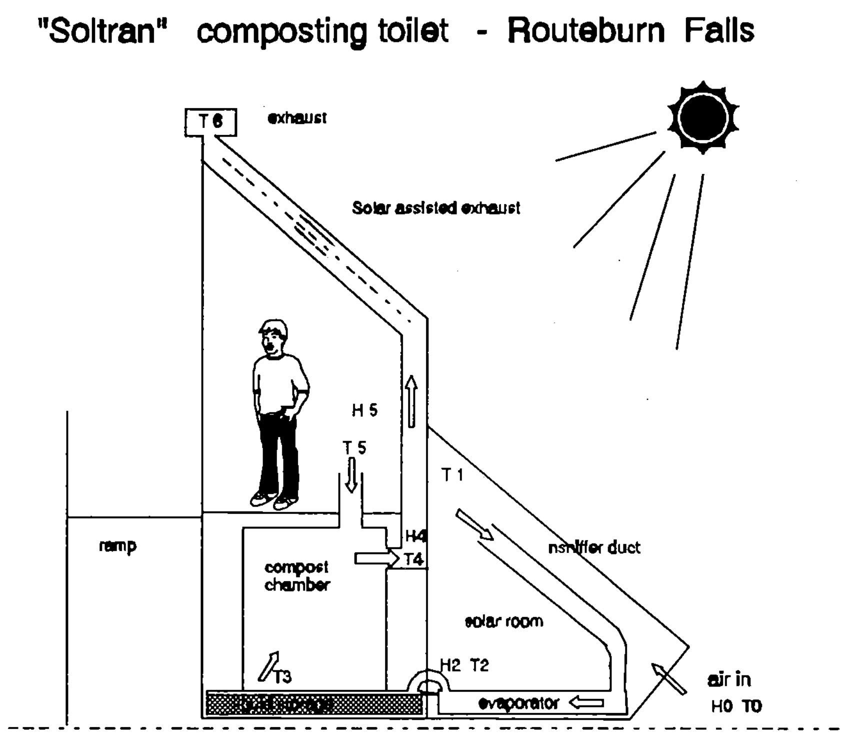


Figure 3.1

T = Temperature sensor

H = Humidity sensor

3.1 METHOD

The sensors were located to allow an energy balance approach to be used for analysis. In calculating the energy balance two problems emerged: first, air flow rate could not be measured automatically at the low flow rates encountered. A full energy balance requires air flow rate to be known, as heat transfer and water removal are affected by it. Air flow rate could, however, be estimated by focusing on the compost room energy balance.

Second: infiltration air entering through the toilet seat and emptying door were influencing the humidity of the exit air. This in turn impacted on the calculation of air flow rate.

3.2 COMPOST ROOM ENERGY BALANCE

Air temperature and humidity were both measured as the air entered (T_2 H_2), and exited (T_4 H_4) the compost room. Other temperature measurements yielded storage changes and conduction losses. The compost room was thus an ideal unit for assessing the air flow rate.

At steady state the energy balance of the compost room has the following components:

$$Energy_{in} = Energy_{out}$$

$Energy_{in}$ is:

- hot moist air (ventilation),
- biological heat production.

$Energy_{out}$ is:

- cool moist air (ventilation),
- conduction.

Ventilation appears as a gain and a loss. Net ventilation will be used on the input side as nost of the time inputs exceed losses.

For steady state the energy balance formula for the compost room can be written as:

$$Q_{ventilation}+Q_{biological}=Q_{conduction} \tag{3.1}$$

Q = Watts

With air temperature and solar radiation changing throughout the day, steady state conditions will never exist. Energy will flow into, or out of, storage as appropriate.

For a non steady state the energy balance is:

$$Q_{storage}=Q_{ventilation}+Q_{biological}-Q_{conduction} \tag{3.2}$$

3.2.1 Ventilation gain (Q_v)

The amount of energy and moisture content in the air at each monitoring point can be calculated if both temperature and humidity are known (ASHRAE, 1989). Any change in the calculated value between two consecutive points represents energy gain or loss, or moisture gain or loss, in the area between the two points.

Saturated vapour pressure can be calculated from:

$$p_{sw}=10^{30.59051-8.2\log_{10}T+(2.4804\times10^{-3})T-\frac{3142.31}{T}} \tag{3.3}$$

T	= absolute temperature	(C)
P_{sw}	= saturated vapour pressure	(kPa)

Vapour pressure can be calculated by proportion from:

$$p_v=\frac{p_{sw}RH}{100} \tag{3.4}$$

where	RH	= relative humidity	(%)
	P_v	= vapour pressure	(kPa)

Moisture content of the air can then be calculated:

$$g = \frac{.62197 p_v}{101.325 - p_v} \tag{3.5}$$

where g = moisture content (kg(H_2O)/kg(dry air))

At higher altitudes the constant 101.325 can be replaced by the barometric pressure for the particular altitude. Routeburn Falls (1000+ metres) will have a barometric pressure of 90 kPa.

Knowing the moisture content, it is then possible to calculate the enthalpy of the air at that point:

$$h = (1.007t - 0.026) + g(2501 + 1.84t) \tag{3.6}$$

where t = temperature (^{0}C)

h = enthalpy (kJ/kg(dry air))

This equation has two components: sensible heat and latent heat.

Sensible heat = (1.007t - 0.026)

Latent heat = g(2501 + 1.84t)

Knowing the dry air moisture content and temperature at each point allows calculation of the water evaporated or condensed in the area between the two points of measurement. Similarly the enthalpy at each point allows calculation of the energy absorbed or released between the two points.

Location 3 (figure 3.1) -liquid storage out- contained a temperature sensor but not an humidity sensor. The state of the air at this point can be estimated if it is assumed that the air is cooled to below saturation point (see figure 3.2). Thus for most of the day $P_{sw}=P_v$. Placing these values in the moisture content formula will give the moisture content of the air. Enthalpy can be calculated knowing the moisture content and temperature.

$$h_3 = (1.007t_3 - 0.026) + g_3(2501 + 1.84t_3) \tag{3.7}$$

3.2.2 Calculation of watts

Watts can be calculated from enthalpy if the mass flow rate is known. Mass flow rate is calculated from the volumetric flow rate:

$$Ma_{inlet} = \frac{V_{inlet}}{specific\ volume(v)} \tag{3.8}$$

Ma	= mass flow rate	(kg/s)
V_{inlet}	= volumetric flow rate	(m^3/s)
v	= specific volume	(m^3/kg(dry))

Specific volume is also a function of temperature and moisture content and is calculated from:

$$v = \frac{8.3144T(1+1.6078g)}{28.9645P} \tag{3.9}$$

where P = total pressure (kPa)

Multiplying mass flow rate by enthalpy difference allows the number of watts absorbed or released to be calculated.

Thus: To calculate the watts supplied to the compost room by the ventilation air:

$$Q_v = (Ma_2h_2 - Ma_4h_4) * 1000 \tag{3.10}$$

Q_v = watts supplied to the compost room by ventilation air.

Similar calculations can be done for any part of the toilet. A positive value indicates energy is *added* to the compost room, a negative value indicates energy is *removed* from the compost room.

3.2.3 Infiltration air

Plotting the initial data on a psychrometric chart, showed that the air exiting the compost tank (location 4; figure 3.2) was not in a state consistent with adiabatic cooling at dew point. The exit humidity was less than 100%, even though the air had cooled to below dew point while travelling through the compost chamber. The reason for the difference was infiltration of external air into the compost chamber, mainly through the commode, but also the poorly sealed emptying door (see figure 3.1). In other words, Ma_2 did not equal Ma_4.

It is possible to estimate the amount of infiltration air from the data:

solar room air (Ma_2) ↘

→ (Ma_4) exhaust

infiltration air(Ma_5) ↗

For two mixing airstreams, their mass flow rates must balance:

$$Ma_4 = Ma_2 + Ma_5 \tag{3.11}$$

Where Ma_5 = mass flow rate of infiltration air (kg/s).

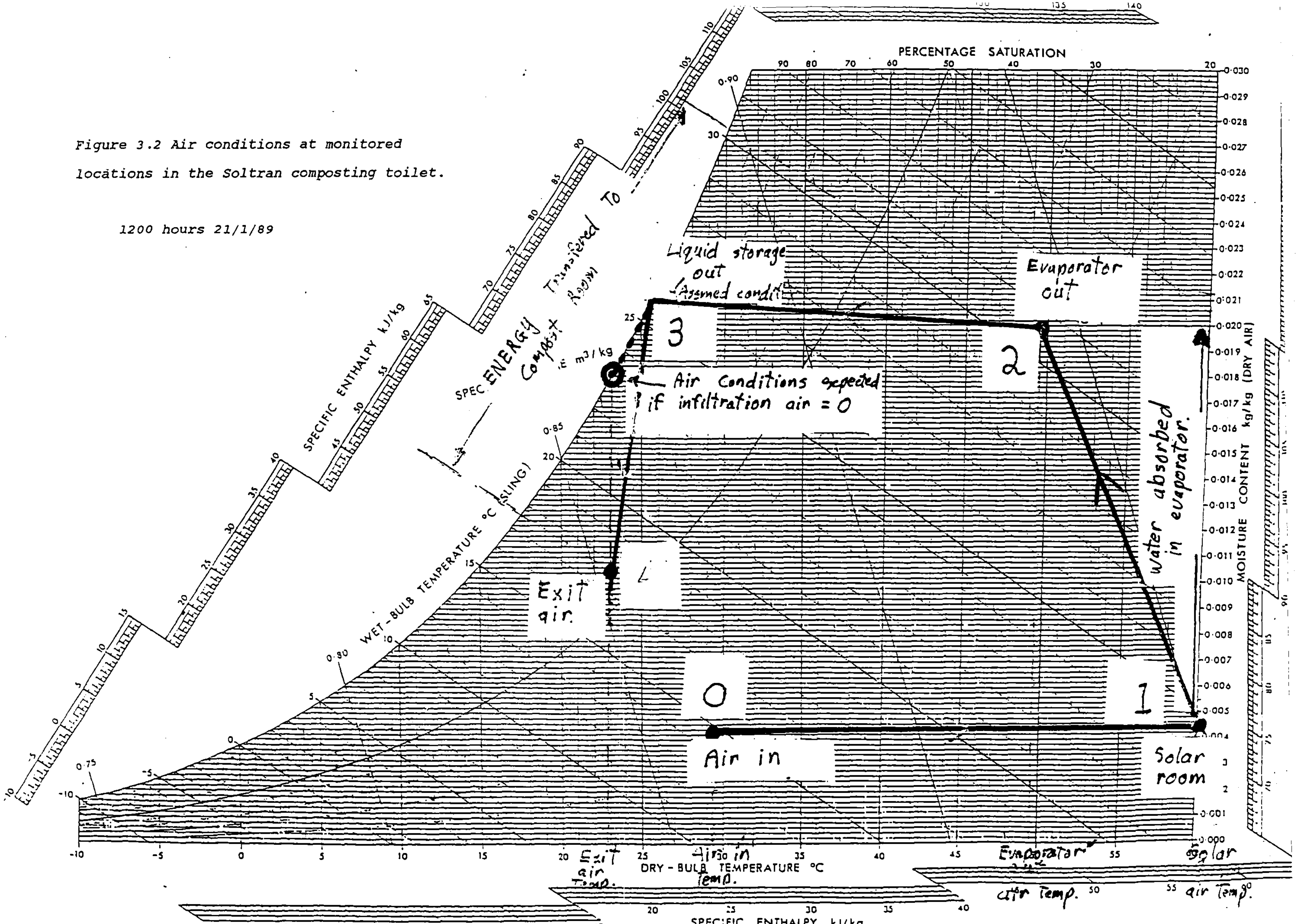
Total moisture must balance:

$$g_4 Ma_4 = g_2 Ma_2 + g_5 Ma_5 + G \tag{3.12}$$

G = water absorbed/condensed in the compost chamber ($kg(H_2O)/s$)

Figure 3.2 Air conditions at monitored locations in the Soltran composting toilet.

1200 hours 21/1/89



Substituting equation 3.11 in equation 3.12 and rearranging:

$$g_5Ma_5=g_4(Ma_2+Ma_5)-g_2Ma_2-G \tag{3.13}$$

$$g_5Ma_5=Ma_2(g_4-g_2)+g_4Ma_5-G \tag{3.14}$$

$$G=Ma_2(g_4-g_2)-Ma_5(g_5-g_4) \tag{3.15}$$

Rearranging allows calculation of infiltration mass flow rate:

$$Ma_5=\frac{Ma_2(g_4-g_2)-G}{(g_5-g_4)} \tag{3.16}$$

G is difficult to establish. However the path for the infiltration air from the commode to the exit duct is short and largely separate from the compost, therefore an estimate of the variation in infiltration rate throughout the day can be made by assuming G=0.

Ma_2 is also unknown, but the ratio of infiltration air to Ma_2 can be calculated by rearranging equation (3.16) (assuming G=0):

$$\alpha=\frac{Ma_{infiltration}}{Ma_{input}}=\frac{Ma_5}{Ma_2}=\frac{g_4-g_2}{g_5-g_4} \tag{3.17}$$

Where: α = the proportion of inlet air that is infiltrated

NOTE: for the compost room energy balance, G will not always equal 0, especially during daylight hours. It would be preferable to know the proportion of infiltration air by measurement. If this were measured then the moisture changes in the compost chamber (G) can be calculated by rearranging equation (3.16):

$$G=Ma_2(g_4-g_2)-Ma_5(g_5-g_4) \tag{3.18}$$

By definition:

$$Ma_5=\alpha Ma_2 \tag{3.19}$$

Therefore equation (3.18) can be written:

$$G=Ma_2[(g_4-g_2)-\alpha(g_5-g_4)] \tag{3.20}$$

Alternatively the moisture per kg air flow can be obtained.

$$\frac{G}{Ma_2}=g=(g_4-g_2)-\alpha(g_5-g_4) \tag{3.21}$$

Conservation of energy means that in equation (3.21), enthalpy is interchangeable with moisture content, hence enthalpy changes within the compost chamber can be calculated. If infiltration rate is known then it would be possible to estimate the amount of heat produced by the compost. To do this, knowing the enthalpy at location 3 would be preferable, as at this point the air will be saturated and at a temperature near to compost temperature.

$$h_{comp}=(h_4-h_3)-\alpha(h_5-h_4) \tag{3.22}$$

Where h_{comp} = enthalpy produced by the compost kJ/kg

and: Watts = h_{comp} * Ma_2 *1000

Enthalpy changes give an accurate view of energy changes within the air flow through the toilet. These are the ventilation effects or Q_v of the full energy balance for the compost room.

3.3 BIOLOGICAL HEAT PRODUCTION Q_b

Two methods of estimating biological heat production are possible:

- from equation (3.22), if infiltration air was measured, and
- from the temperature differential between the edge and the middle of the compost.

The latter method uses the results of Incropera and DeWitt (1985). They derived a formula for calculating temperature distribution in a solid cylinder with heat generation throughout the cylinder:

$$t_r = \frac{q r_0^2}{4k}\left[1 - \frac{r^2}{r_0^2}\right] + t_s \tag{3.23}$$

Where:	q	= rate of energy generation	(W/m^3)
	r_0	= cylinder radius	(m)
	k	= thermal conductivity	(W/m.K)
	t_s	= surface temperature	(^0C)
	t_r	= temperature at point r	(^0C)

If r = 0 then $t_r = t_0$ (temperature at the centre of the pile) and equation (3.23) becomes:

$$t_0 = \frac{q r_0^2}{4k} + t_s \tag{3.24}$$

To relate the surface temperature (t_s) to air temperature (t_a), the surface resistance effect is incorporated. Temperature drop over the surface resistance can be calculated by rearranging the conduction equation (3.32):

$$t_s = \frac{Q}{UA} + t_a \tag{3.25}$$

Q	= Energy lost	(W)
t_a	= air temperature	(^0C)

Substitute (3.25) in (3.24):

$$t_0 = \frac{q r_0^2}{4k} + \frac{Q}{UA} + t_a \tag{3.26}$$

Q (W) can be related to q (W/m^3) by:

$$q=\frac{Q}{volume}=\frac{Q}{\pi r_0^2 H} \tag{3.27}$$

H = cylinder height (m)

And equation (3.26) becomes:

$$t_0=\left(\frac{\left[\frac{Q}{\pi r_0^2 H}\right]r_0^2}{4k}+\frac{Q}{UA}\right)+t_a \tag{3.28}$$

$$t_0=Q\left[\frac{1}{4\pi Hk}+\frac{1}{UA}\right]+t_a \tag{3.29}$$

Rearranged to give watts lost by conduction:

$$Q=\frac{t_0-t_a}{\frac{1}{4\pi Hk}+\frac{1}{UA}} \tag{3.30}$$

The temperature of the pile was typically 7^0C above the air exiting the compost chamber. If the following assumptions are made:

The chambers are half full - H	= 0.6 m
Cylinder radius	= 0.6 m
Surface area is then	= 4.52 m^2
Compost conductivity	= 0.2 W/m.K (Tollner and Verma, 1987)
Surface resistance R = .12 therefore U = 1/R	= 8.33 W/m2.K

$$Q=\frac{7}{\frac{1}{4\pi\times.6\times.2}+\frac{1}{8.33\times4.52}}=10\ watts \tag{3.31}$$

3.3.1 Theoretical rate of heat production

Lentner (1981), measured the energy in faeces from 21 humans. He found 0.58 MJ/person.day (21.5 MJ/kg(dry) was produced. It is also known that 36% of the dry matter is oxidised in composting (see chapter 4), therefore 0.2088 MJ/person.day is available to be released during composting.

This energy will be released over a period of time and, as a toilet is in continuous use, there will be fresh additions daily. If the number of days for which any particular faeces produces heat is termed d, and it is assumed that the rate of heat output is constant, then each day's contributions will produce 0.2088/d MJ/person.day. If the number of people using the toilet = y then the daily heat output will be 0.2088*y/d MJ/day.

Several days of contributions will each add their energy, so the total energy output for the toilet will increase as each day is added, until sufficient time has elapsed for the first contributions to become exhausted and cease contributing heat. This will be after d days and the total amount of heat produced will be the sum of all the individual contributions:

$$Q_{total} = \Sigma(0.2088*y/d_{day\ 1} + ... 0.2088*y/d_{day\ d})$$

$$= 0.2088*y/d*(1+1+.....d)$$

$$= 0.2088*y \text{ MJ/day}$$

$$= 2.42*y \text{ Watts}$$

Thus the rate of heat output in a continuous use toilet, is independent of the time taken to breakdown, but directly dependent on the number of users.

For a usage rate of 12 people/day:

$$Q_{total} = 0.2088*12*10^6/86400 \text{ Watts}$$

$$= 30 \text{ Watts}$$

This figure is higher than the estimated heat production from equation 3.31 (10 Watts), which suggests that composting could proceed further. Trials at Lincoln University, in which poorly decomposed Soltran compost was compared to fresh human waste, showed actual decomposition being approximately half of potential decomposition (see section 4.4).

3.4 CONDUCTION LOSSES Q_c

Conduction losses can be calculated from the formula:

$$Q = UA(t_{inside} - t_{outside}) \tag{3.32}$$

Q	= Watts	(W)
U	= Heat transfer coefficient	(W/m^2K)
A	= Conductive area	(m^2)

U is calculated as the inverse of the sum of the thermal resistances.

$$U = \frac{1}{\sum R} \tag{3.33}$$

Several different temperature measurements can be used to increase the accuracy of the estimate of conduction losses. These can be divided into two areas (1) losses from the compost carousel, and (2) losses from the liquid storage.

3.4.1 Losses from the compost carousel

The average of the air temperatures at liquid storage out (t_3) and compost out (t_4) are used, hence all resistances from the outside to the inside of the compost chamber must be used:

$U = 1/(R_{so} + R_{tin} + R_{batts} + R_{polystyrene} + R_{paper} + R_{airspace} + R_{fibreglass} + R_{si})$

Where R_{so} & R_{si} are internal and external surface film resistances.

In this manner conductive losses were calculated for:

Roof (using CR10 temperature)

Solar room wall (using solar room temperature)

External walls (using external air temperature)

3.4.2 Losses through the floor

A different U value had to be used for the floor as the liquid storage tanks covered the entire floor. Liquid temperature was measured in the middle of the liquid storage tank (figure 3.3). Thus there is a need to replace the internal surface resistance (R_{si}) above with a water resistance (assuming there will be no thermal mixing of the water and all heat movement is by conduction).

Thus: R_{si} is replaced with l/k_{water}

l = water distance from thermometer to bottom of container (metres).

k_{water}= thermal conductivity of water (W/m.K)

3.5 STORAGE CHANGES Q_s

The energy flows are not steady state, hence storage changes must enter the energy balance picture.

Sufficient locations contained temperature sensors to estimate storage changes:

Watts = (mass*specific heat*temp change)/time

Where: temp change = $t_{(time+1)}-t_{(time-1)}$

Thus heat flowing *into* storage will be positive and flowing *out of* storage will be negative. Note: due to the small changes involved temperature change over 2 hours was used.

Liquid storage provides the greatest proportion of total storage (83%) and is the most difficult to measure accurately.

The thermal mass of the components are:

component	Quantity	C_p	Thermal mass kJ/K	%
Water	407 kg	4190 J/kg.K	1705	83
Compost (variable)	50-400 kg	1000 J/kg.K	50-400	2-17
Components	100 kg	840 J/kg.K	84	4
Insulation	16 m^2	2 $J/m^2.K$	.032	-
Building material	100 kg	2090 J/kg.K	209	10

Table 3.1 Thermal mass of components within the compost room.

3.5.1 Calculating liquid storage changes

With hot air flowing across the top of the tank, hot water will remain at the surface and thermal mixing will not occur. A temperature gradient will exist from the top of the tank to the bottom. The liquid temperature as measured (T_L figure 3.3) will be part of this profile, thus an increase in liquid temperature at the sensor location will not be matched by an identical temperature increase at all parts of the profile (some areas, those above the probe, will show a greater increase while those areas below the probe will increase less). Hence it is not valid to multiply the measured temperature change with the thermal mass.

This problem would be overcome if the enthalpy change in the airflow within the tank was all absorbed in the water (then enthalpy changes could be used to calculate storage). This is not the case as some heat will be lost through the surface of the tank (although this is insulated in parts).

The other approach is to treat the liquid within the tank as a conducting medium, calculate heat transfer coefficient U (surface resistance + conductivity of the liquid), between the two thermometers. Then knowing the two temperatures, U, and the tank area, the watts transferred to the liquid can be calculated.

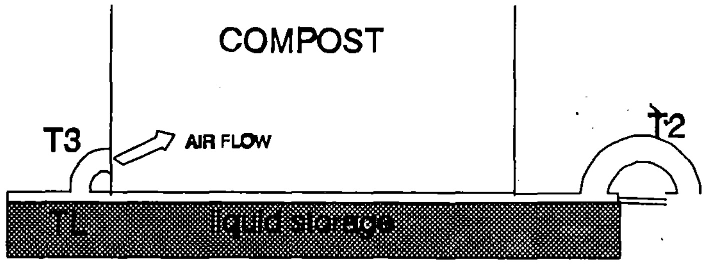


Figure 3.3 Temperature sensor locations in the liquid storage.

A further complication arises in that the temperature of the air entering the tank is substantially different from the temperature leaving the tank. Fortunately the two temperature measurements are at both extremes of the air flow across the tank, and if one assumes that thermal buoyancy will even up any temperature differences in the surface of the water. Then averaging the two air temperature measurements will be valid.

$$Q=UA\Delta t=UA(\frac{t_2+t_3}{2}-t_L) \tag{3.34}$$

An error will occur when the air is cooled below dew point and condensation occurs. The heat transferred in this way would not be accounted for in equation 3.34. Fortunately most of the condensation seems to occur in the compost carousel, hence this source of error is likely to be small.

3.6 CALCULATING AIR FLOW RATE

Of all the energy balance components, ventilation gain or loss is the only one dependent on air flow through the system. Knowing the ventilation gain one is able, via the enthalpy difference within the compost chamber (liquid storage + compost), to calculate the velocity of the air within the inlet duct by rearranging equation 3.2 i.e.:

$$Q_{ventilation}=Q_{storage}-Q_{biological}+Q_{conduction} \tag{3.35}$$

$$Q_v=Ma_2h_2-Ma_4h_4 \tag{3.36}$$

By definition:

$$Ma_4=Ma_2+Ma_5 \tag{3.37}$$

and:

$$Ma_5=\alpha Ma_2 \tag{3.38}$$

Therefore equation 3.37 can be written:

$$Ma_4=Ma_2+\alpha Ma_2 \tag{3.39}$$

Substituting equation (3.39) in equation (3.36)

$$Q_v=Ma_2h_2-(Ma_2+\alpha Ma_2)h_4 \tag{3.40}$$

$$Q_v=Ma_2(h_2-(1+\alpha)h_4) \tag{3.41}$$

$$Ma_2=\frac{Q_v}{h_2-(1+\alpha)h_4} \tag{3.42}$$

Substituting Q_v from equation (3.35) in equation (3.42)

$$Ma_2=\frac{Q_s-Q_b+Q_c}{h_2-(1+\alpha)h_4} \tag{3.43}$$

If there is no infiltration air $\alpha = 0$.

Thus flow rate is affected by any error in calculating alpha. An error is known to occur as equation 3.17 assumes G=0, and this is likely to be incorrect around mid-day. Actual infiltration was able to be measured at high flow rates only, as the vane anemometer used was not effective at low airspeed, and the hot wire anemometer could not be positioned appropriately with the toilet lid closed.

Results of the vane anemometer measurements are:

Flow into duct	1.1 m/sec
Area of duct	0.03168 m^2
Infiltration through toilet seat	0.53 m/sec (lid closed)
Infiltration through toilet seat	0.9 m/sec (lid open)
Area of stand pipe	0.03142 m^2

Proportion infiltrated (alpha) = 0.53*0.03168/(1.1*0.03142) = 0.48

Two anomalies occur if alpha remains constant throughout the day.

1/ Estimating alpha from equation (3.17) indicates infiltration proportion rises as temperature increases (air flow increases). The equation gave infiltration rates up to 3 times flow rate in the duct. This figure was not confirmed by measurement. The anomaly occurred because some moisture is evaporated in the middle of the day (G > 0).

2/ Negative values of F (where: F is the constant that relates flow velocity and temperature difference between chimney and outside air - see equation 3.45) occurred on cloudy days if alpha was calculated using equation 3.17 (see section 3.6.1).

Thus a better estimate of infiltration air (alpha) was needed. Logic suggests that at zero temperature differential between chimney temperature and outside air, there would be no flow of air up the chimney and hence alpha = 0. Measurement shows that at high flow rates alpha = 0.5. Therefore if infiltration varied linearly between 0 and 0.5 as temperature difference (t_6 - t_0) rose from 0^0C to 50^0C, then alpha could be estimated by the formula:

$$\alpha = (t_6 - t_0) * 0.5/50 = (t_6 - t_0) * .01 \qquad \textbf{(3.44)}$$

This gave consistent F values between hot and cold days (see table 3.2).

Calculation of ventilation rate using alpha from equation 3.44 in equation 3.43, shows some instability just after sunrise and from mid afternoon on. The method is only valid for steady state conditions (instability occurs when heat flows are changing direction). A more stable airflow estimate would be preferable for the energy balance. Stability was achieved by correlating airflow, as calculated above, to measured temperatures.

3.6.1 Correlation of airflow to temperature difference

Thermal ventilation is dependent on the temperature difference between inlet (ambient) and exhaust air, and the height difference between the inlet and outlet. The stack equation also indicates that if the temperature difference is zero then air flow will be zero. For the toilet, exhaust temperature (t_6), and the temperature of the lower half of the chimney were measured (t_4). A correlation was possible between exhaust temperature and ventilation rate, as calculated with equation 3.43 (converted to the linear measurement m/s, by multiplying mass flow rate with specific vol and dividing by the duct cross sectional area). Four hot days and three cold days (January and February 1989) were used.

Various combinations of temperatures were tried (exhaust (t_6) only, average of exhaust (t_6) and compost-out (t_4), average of exhaust and compost-out minus external air(t_0)). Of these the average of exhaust and compost-out minus external air, zero forced, was found to best fit both hot and cold days.

$$flow\ rate = F[\frac{(t_6+t_4)}{2} - t_0] \tag{3.45}$$

where F = constant

flow rate = m/s

From these correlations, F was calculated at 0.0123 (see table 3.2) and the equation used for air flow through the toilet was:

$$flow\ rate = .0123[(\frac{t_6+t_4}{2}) - t_0 \tag{3.46}$$

This equation gave a minimum flow rate of 0.05 m/s rising to 0.3 m/s on a hot day. This agrees reasonably well with measurements made by hot wire anemometer in November 1991 which indicated a night time flow rate of 0.1-0.2 m/s rising to 0.2-0.3 m/s during a hot day.

DAY	F	r^2
29 January (hot)	.0186	.33
6 February (hot)	.0158	.22
7 February (hot)	.0147	.52
8 February (hot)	.0108	.14
27 January (cold)	.0096	.12
31 January (cold)	.0188	.07
2 February (cold)	.0204	-.01

Table 3.2 - F (the constant relating flow velocity to temperature difference) as calculated by correlation of airflow (equation 3.43) using alpha calculated from equation 3.44, with temperature difference (equation 3.45).

3.7 ASSESSING TOILET PERFORMANCE

The toilet heat flow system is designed to meet two objectives i.e. evaporate liquid and heat the compost. Once airflow has been calculated using equation 3.46, an accurate energy balance is possible on a half hourly basis. The energy balance data can then be used to calculate:

1/ the overall evaporation performance,

2/ the amount of heat transferred to the compost room,

3/ the amount of available sunlight utilised (efficiency).

3.7.1 The overall evaporation performance

Subtracting the moisture content of the air entering the toilet (g_0) from the moisture content of the air leaving the toilet (g_4) and multiplying by the mass flow rate allows the overall evaporative performance to be assessed (equation 3.20).

In addition the amount of energy (Joules) in the evaporated water can be obtained by using only the latent heat portion of equation (3.6):

$$\text{evaporative joules} = \text{latent heat}_{out} - \text{latent heat}_{in}$$

But the mass of air out is different from mass of air in (infiltration). Thus to calculate the energy in the evaporated water:

$$Q_e = g_4(2501 + 1.84t_4)(Ma_1 + Ma_5) - (g_0(2501 + 1.84t_0)Ma_1) \tag{3.47}$$

Q_e = evaporative energy (kW)

From equation (3.19)

$$Ma_5 = \alpha Ma_1$$

Substituting in Equation (3.47)

$$Q_e = Ma_1[g_4(2501 + 1.84t_4)(1 + \alpha) - g_0(2501 + 1.84t_0)] \tag{3.48}$$

3.7.2 Compost room performance

An intended feature of the design is for heat to be transferred from the solar room to the compost room. The amount of heat transferred can be assessed by the difference between the enthalpy of the air entering and leaving the chamber.

Figure 3.2 indicated that some water may be condensed in the compost room. Heat is released when this water condenses. It is possible to separate the heating contributions of warm air from condensation of water vapour, by separating the sensible and latent heat portions of the enthalpy formula (equation 3.6).

Thus sensible (warm air) heating of the compost room = sensible heat_{in} - sensible heat_{out}.

$$Q_{cs} = Ma_2[(1.007t_2 - .026) - (1.007t_4 - .026)(1+\alpha)] \tag{3.49}$$

Q_{cs} = heat added to compost room by sensible heat loss from the ventilation air (kW).

Latent heating of compost room (condensation of water vapour) = latent heat$_{in}$-latent heat$_{out}$.

$$Q_{cl} = Ma_2[g_2(2501+1.84t_2) - g_4(2501+1.84t_4)(1+\alpha)] \tag{3.50}$$

Q_{cl} = heat added to compost room by latent heat loss from the ventilation air (kW).

The total heating contribution to the compost room = sensible heat + latent heat.

3.7.3 Overall efficiency

It is possible to calculate the overall efficiency in use of available sunlight.

$$EFFICIENCY = \frac{USEFUL\ ENERGY}{ENERGY\ INPUT} \tag{3.51}$$

Energy input (solar radiation) is known, from either measurement or solar geometry calculations and biological heat production is small compared with solar sources.

Total useful energy is found by adding net evaporation (Q_e), to the compost room heating (Q_{cl} + Q_{cs}). Dividing the amount utilised with the amount falling on the solar room collector gives an estimate of the overall efficiency of the toilet.

$$Efficiency_{(instantaneous)} = \frac{Q_e + (Q_{cl} + Q_{cs}).}{solar\ radiation(Watts)} * 100 \tag{3.52}$$

Double counting of evaporation contributions (some is condensed in the compost room and appears as heating) is avoided as net evaporation Q_e = evaporation from the solar room, minus condensation in the compost room. In other words, the value for net evaporation is less than the amount of liquid evaporated from the evaporator.

Biological heat production (Q_b) occurs within the compost chamber and will raise the enthalpy of air exiting the chamber. For an accurate assessment of efficiency a proportion of the biological heat production should be deducted from Q_v. i.e.

$$Q_v = Q_{vs} + Q_{vb}$$

where Q_{vs} = ventilation energy from solar (W)

Q_{vb} = ventilation energy from compost (W)

The proportion of energy produced from the compost that is lost via ventilation compared to conduction is not known. Biological heat production produces about 0.9 MJ/day compared with 12 MJ/day for net evaporation and 7 MJ/day heating of the compost chamber for a sunny day. So even if all the biological heat was lost via ventilation this would represent only 5% of the total hot day energy. For a cold day the biological heat production would remain the same (.9 MJ), but net evaporation drops to 2 MJ/day and heating of the compost chamber is negligible. So biological heat production rises to 45% of the total flows. One would expect conduction losses to be higher for a cold day but the proportion of biological heat that is lost by ventilation remains unknown. Efficiency is assessed as if all the ventilation heat flows were from solar sources and thus efficiency will be overestimated.

The effective glazing area was 4.4 m^2 (half of the solar room glazing area, there being two compost tanks utilising heat from the one solar room) therefore:

$$W/m^2 \times 4.4m^2 = Watts \qquad \textbf{(3.53)}$$

Efficiency is best assessed on a daily basis as considerable heat is stored in the solar room and contributes to both evaporation and compost room heating for most of the night.

The overall efficiency is then calculated from:

$$Efficiency_{(day)} = \frac{kJ_{utilised/day}}{kJ_{arriving/day}} \times 100 \qquad (3.54)$$

The data is in half hour lots, therefore it must first be converted from Watts (Joules/sec) to Joules/half hour by multiplying by 1800. Then all half hour lots for each day, can be summed:

$$kJ_{utilised/day} = \sum_{time=0}^{2330} ((Q_e + Q_{cl} + Q_{cs}) * 1800) \qquad (3.55)$$

3.8 RESULTS

3.8.1 Climate and data summary

Weather observations, for the summer months (November to May), noted in the warden's diary indicate that about 1/3 of the days are sunny, 1/3 partly cloudy, 1/3 wet and cold.

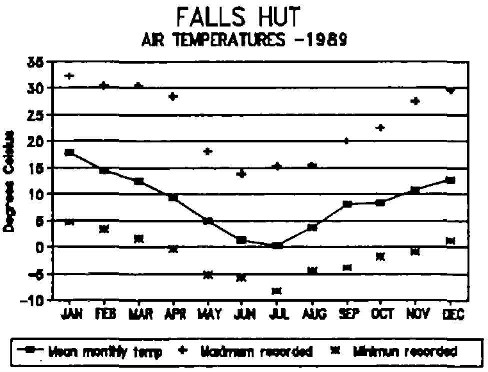


Figure 3.4 The monthly, mean, maximum and minimum air temperatures

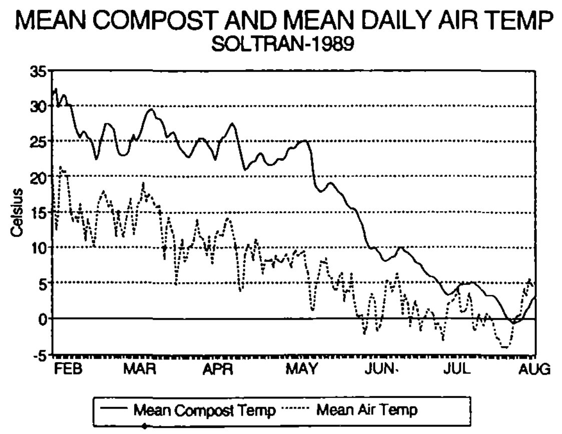


Figure 3.5 The fluctuation of mean daily compost temperature with mean daily air temperature. Note: the toilet was closed at the end of May.

The effect of a hot sunny day on humidity and temperatures within the toilet can be seen in figures 3.6 to 3.8.

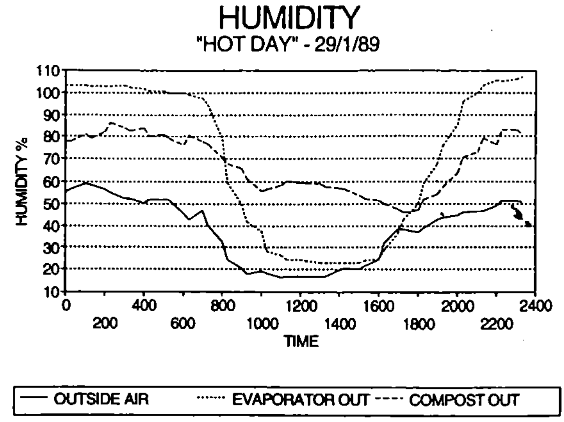


Figure 3.6

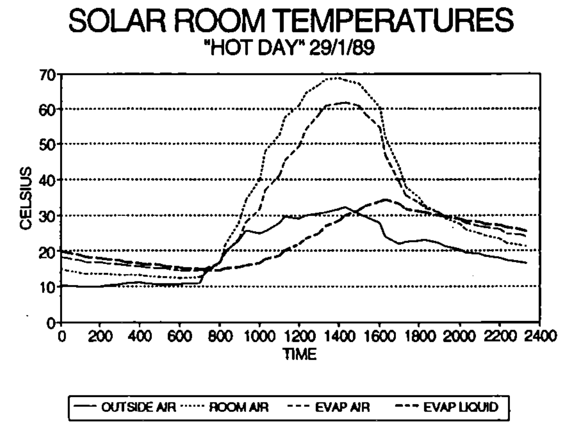


Figure 3.7

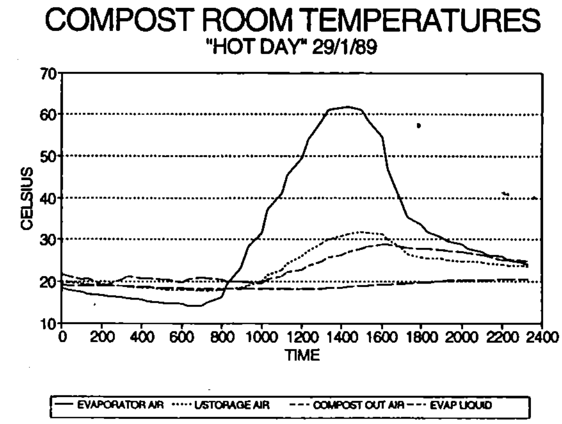


Figure 3.8

Note: the evaporator air temperature occurs in both figure 3.7 and figure 3.8 as this is the state of the air as it exits the solar room and enters the compost room.

3.8.2 SOLTRAN DAILY PERFORMANCE

3.8.2.1 Energy use on hot and cold days

Figures 3.9 to 3.12 show the daily performance of the Soltran for various parameters of interest to this thesis. A period of 15 days immediately after the monitoring was installed was chosen for intensive analysis (27/1/89 -10/2/89). This period was chosen for two reasons: first, it covered two periods of hot weather and one period of cold weather, and second, the humidity sensors' reliability were known (they had "drifted" by the end of the first year, but it is uncertain when drifting began).

3.8.2.2 Net water evaporation

Net water evaporation rose from almost nil on the coldest day to a high of 4 kg. per day on the hottest day. The evaporator was able to evaporate over 6 kg. on sunny days, but 2 kg. was condensed in the compost room (figure 3.9).

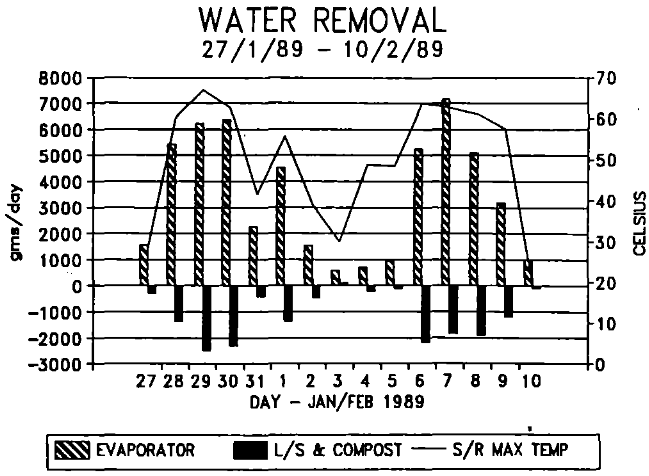


Figure 3.9 Daily water removal from the evaporator and compost room (liquid storage (L/S) & compost), as influenced by the maximun solar room (S/R) temperature.

3.8.2.3 Compost room heating

Compost room heating can be separated into the heating effect of hot air and the heating effect of condensing water (figure 3.10).

Hot air was able to contribute 3000 kJ of heat to the compost room on a hot day, however on a cold day there was a net removal of heat by the air.

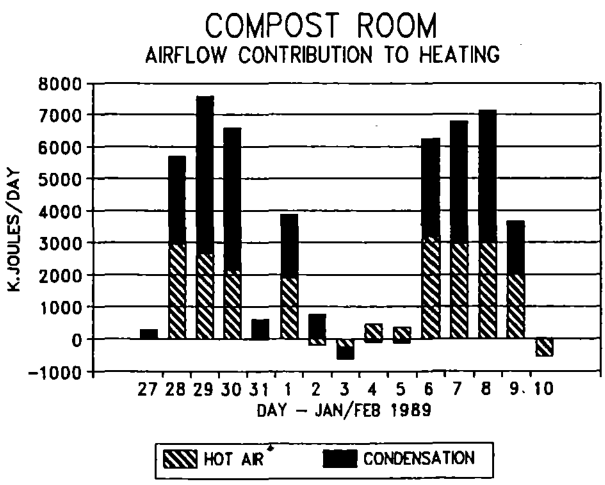


Figure 3.10 Airflow contribution to heating of the compost room.

Water condensation consistently contributed more heat than hot air (figure 3.10).

Figure 3.11 shows that more energy was used in evaporation, than in heating of the compost chamber.

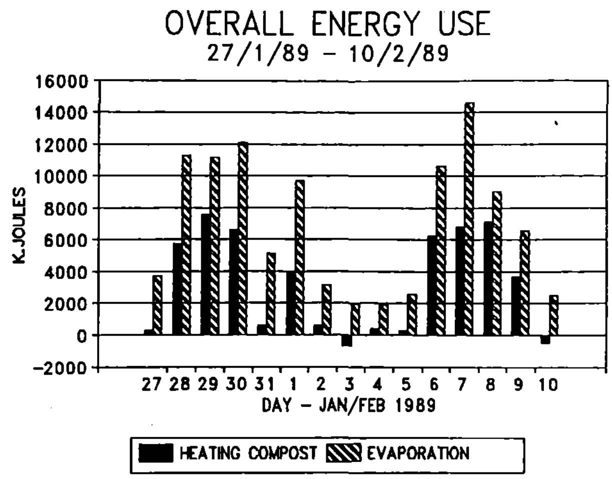


Figure 3.11

3.8.2.4 Overall efficiency (utilisation of sunlight).

The solar radiation instrumentation was not installed until later in the monitoring programme. Because of the unreliability of the humidity sensors at this time, solar radiation data was superimposed on the early data by using data from days that had similar solar room maximum temperatures. The instrument measured total radiation (long wave and short wave), so short wave radiation (sunlight) was estimated by subtracting long wave radiation of 260 watts (typical night time radiation reading). Use of total radiation was 10% on sunny days, falling to very low levels on cloudy days (figure 3.12). If only shortwave radiation (sunlight) data is used in equation 3.51 then

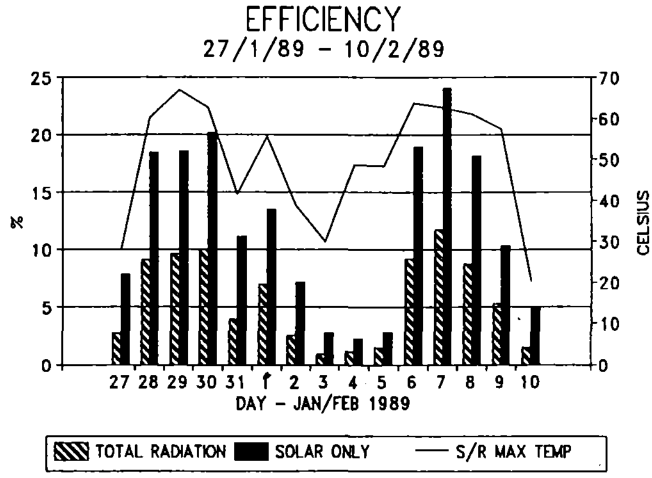


Figure 3.12

efficiency rises to around 20% for a hot sunny day. The toilet does not use radiation efficiently.

3.8.3 SOLTRAN HOURLY PERFORMANCE

3.8.3.1 Net water evaporation

The performance throughout the day of the evaporator, and how much water is condensed in the compost room, can be seen in figure 3.13(hot) and 3.14(cold).

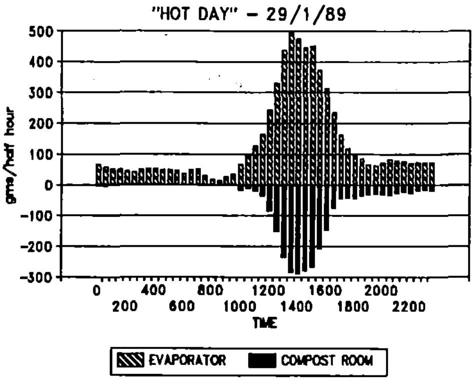


Figure 3.13 Evaporation throughout a hot day.

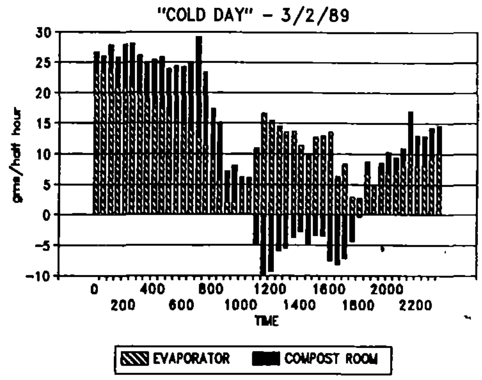


Figure 3.14 Evaporation throughout a cold day

Evaporation rate rises to a peak at 1400 hours. This is after solar maximum, as evaporation rate closely follows the increase in temperature of the evaporator liquid, which itself lags behind solar room temperature.

3.8.3.2 Compost room heating

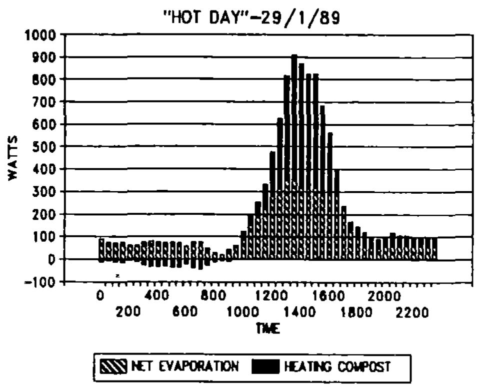


Figure 3.15 The energy transfered to the compost room - hot day

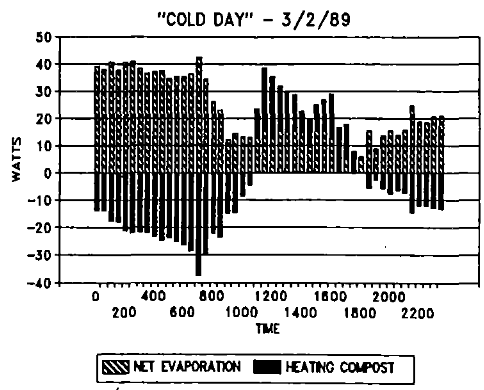


Figure 3.16 The energy transfered to the compost room - cold day

3.8.4 ENERGY TRANSFER WITH FAN ON

The humidity sensors were replaced on 8/2/92. By this time, fans had been installed to try to overcome the evaporation problem. The fans were installed in the compost chamber air exit manifold (location 4 - figure 3.1), and sucked air through the compost chamber. It is possible to see the effects of the fan, by comparing a hot day in February 1992 (fan operating) with a hot day in January/February 1989 (fan not operating - figure 3.17 to 3.19).

Whether the fan was on or off was not recorded by the logger, however the thermostats were set to turn the fan on when the solar room reached 30^{0}C. It is further known, from both hot wire and vane anemometers that the duct velocity rose to 0.7 m/s when the fans were on. The airflow formula in the energy balance (equation 3.46) was replaced with a fixed flow rate of 0.7 m/s while the solar room was above 30^{0}C.

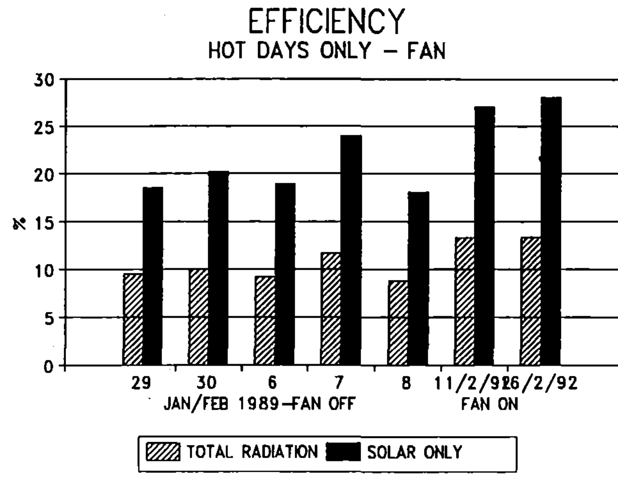


Figure 3.17

Figure 3.17 shows that efficiency is increased with the fan on, but figure 3.18 shows there is no increase in evaporation. Heat transfer by hot air is increased with the fans installed, but there appears to be no increase in net evaporation. The differences can be seen on a half hour basis by comparing figure 3.19 with fig 3.15).

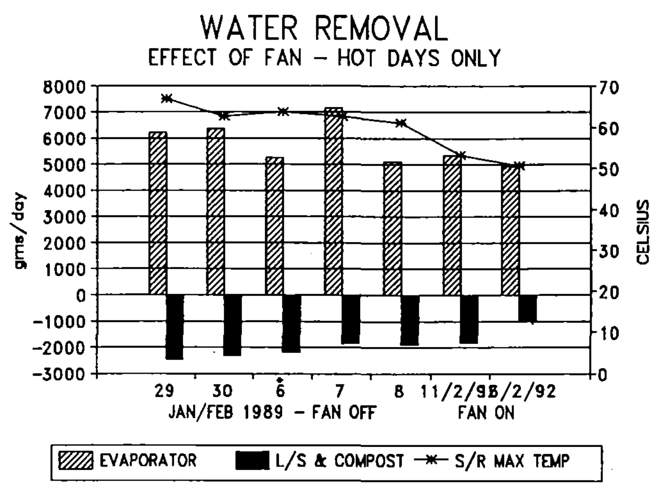


Figure 3.18

The reason for very little effect on evaporation is not entirely clear and was not expected, although field staff had noted that the tanks have still had to be drained even after the fans were installed. This was attributed to low sunshine hours. A number of reasons could explain the lack of increased evaporation:

1/ Solar room temperatures are lower with the fans operating (figure 3.18). This is because the solar room has a greater throughput of air. Lower air temperatures would evaporate less water in the evaporator tanks. It is possible that the drop in evaporation due to lower temperatures is similar in magnitude to the increase in moisture removal due to increased air flow.

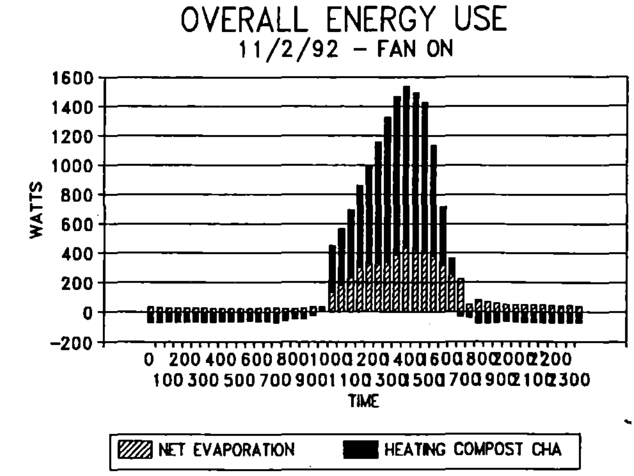


Figure 3.19 The overall energy use with the fans operating

2/ It is possible there was no liquid in the evaporator tanks. The tanks had been drained on 12/1/92 (1 month previously) and the liquid temperatures indicate that liquid levels were still below the sensor. However, about 12 mm of liquid remain in the tank after draining; all previous evidence suggests that inputs exceed evaporation, so the level should have risen in the month since draining. The tanks have never been completely dry in the middle of the season before. Liquid levels are certainly low, but nil liquid is not possible and can be discounted as a cause.

3/ The hot air could 'short circuit' i.e. avoid contact with the liquid. This could occur when thermal stratification and laminar flow of the air in the evaporator tank, reduces mixing of the hot air immediately beneath the cover with cooler moist air at the liquid surface. The evaporator tank cover was stainless steel painted black, and would warm the upper layer of air by conduction, while the lower layer of air would be cooled by evaporation. In addition, the duct removing air from the evaporator tank is on the top of the tank and could be preferentially removing the hot, low moisture content air, from the top of the tank. In effect dry air would 'short circuit' the liquid surface.

With this scenario, diffusion of water vapour upwards from the liquid surface would limit evaporation, and reduce the effect of increased air flow rates. Humidity changes indicate this could be occurring (figure 3.20).

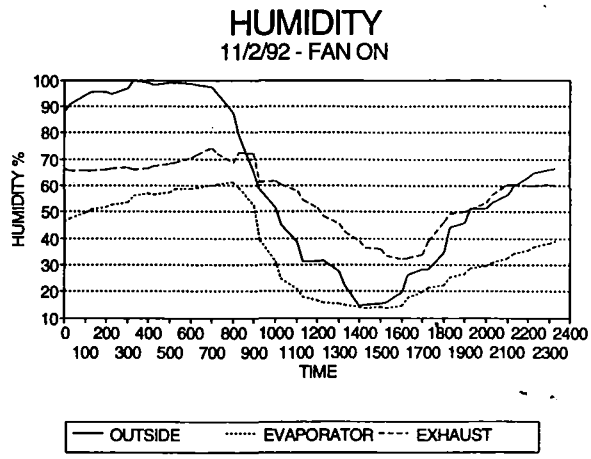


Figure 3.20 The effect of the fan on humidity within the Soltran. Compare to figure 3.6.

4/ Condensation in the compost room limits water removal from the toilet.

This limitation has been discussed previously. The data shows that up to 2 kg of water is condensed in the compost room per day (figure 3.21). However, removal of water has two components: mass flow rate and moisture content. Of these, only moisture content is affected by this limitation. The moisture content at dew point is determined by air temperature not air flow, it should be the same whether the fan is on or off. If moisture content remains the same but flow rate is increased, then net evaporation should be increased. We know that net evaporation has not increased and mass flow rate has increased therefore compost room condensation can be eliminated as a cause.

Of the four reasons discussed the most likely seems to be either the thermal stratification of air flowing through the evaporator tanks, or the lower solar room temperatures noted with the fans on. That is, it is more likely to be an effect on the evaporation side, rather than an effect on the condensation side of the mass balance.

3.9 EVAPORATOR IMPROVEMENTS

3.9.1 Heating potential

The daily change in humidity at H_2 (evaporator), figure 3.20, indicates that there is plenty of potential to increase evaporation. If this were increased, the existing airflow could transfer extra heat to the compost room and, with increased warmth in the compost room, extra water would be carried out the exhaust.

	Enthalpy @ (humidity) (kJ/kg(dry))	Enthalpy @ 100% humidity (kJ/kg(dry))	difference kJ/kg(dry)
air in	42.3 (20)	91.2	
evaporator out	141.7 (23.4)	482.9	341.20
compost out	57.8 (58.7)	81.8	24.00

Table 3.3 The heating potential of saturated air.

Thus at 1300 hrs on a hot January day an extra 340 KJ/kg(dry air) * 0.009 kg/s = 3.06 kilowatts could be transferred if the air was saturated at the evaporator (temperature of the air remains the same). This rate of heat transfer could be achieved with thermal ventilation rates without a fan. In reality no evaporator would give 100% humidity, but the potential for using latent heat of evaporation and condensation as a heat transfer method in low airflow situations should be noted.

The linking of heat transfer, via evaporation and condensation, with water purification (distillation) is a possibility that begins to emerge. With this potential in mind, improving the evaporator performance was seen as one way of improving the overall toilet performance, both evaporation and heating of the compost room.

3.9.2 Background to the design - observations

The original design consisted of a large stainless steel tank with a stainless steel top and two baffles inside to increase the distance the air flowed across the liquid (see photo 3.2).

Observations made include:

1/ The existing evaporator is often full and hence has a high thermal mass, so the liquid does not get hot.

2/ Evaporation rate increases throughout the day as the liquid temperature increases.

3/ The existing evaporator has a stainless steel top, painted black, which prevents direct solar heating of the liquid in the tanks. The liquid is heated by both: radiation from the underside of the tank top and heat transfer from the hot air passing over its surface.

4/ The dew point of the air exiting the compost chamber is limiting water removal from the toilet.

5/ With the dew point being below air temperature, excess moisture is condensed in the compost room. Thus water is cycled from the evaporator tank to the liquid storage tank as moist air, and then some is condensed and returns as water to the evaporator tank via the hose junction.

6/ With improved evaporator efficiency the air entering the compost room would be at a higher enthalpy (it may not have a higher temperature). The greater heat transfer to the liquid storage and compost chamber would warm the chamber and allow the exit air to carry more moisture.

7/ The design must be maintenance free ie. it must not be affected by the residual salts which will accumulate, nor require regular replacement (most people do not relish maintenance on a toilet).

Photo 3.2 - The evaporator (with lid removed) - before modification

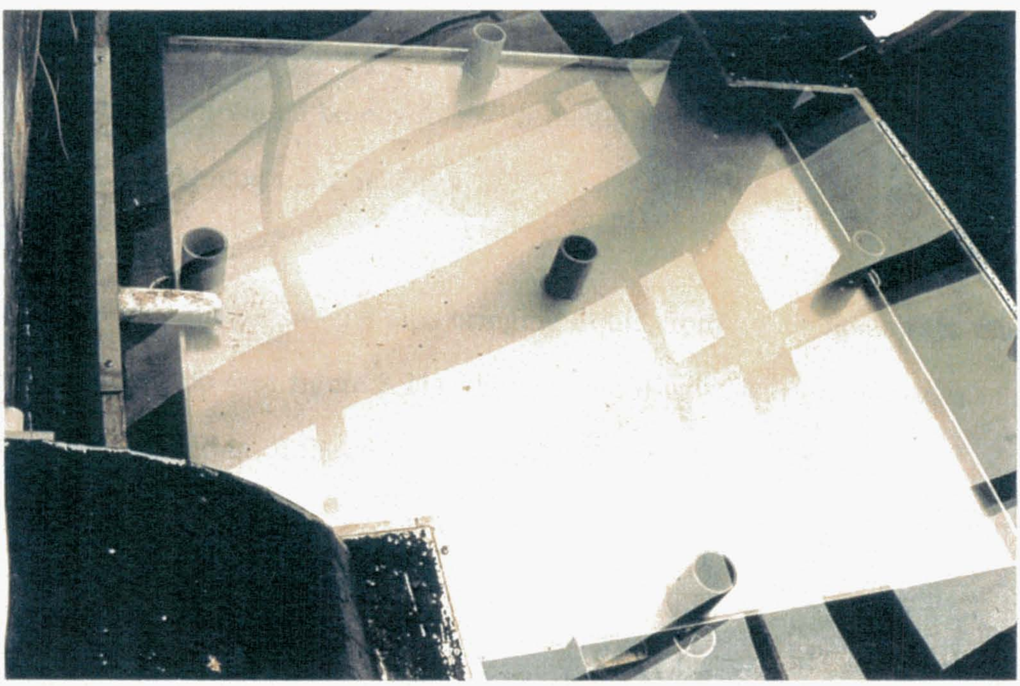


Photo 3.3 The modified evaporator tanks

3.9.3 The design

Mass transfer theory indicates that increasing the surface film temperature of an evaporating liquid will substantially increase the rate of evaporation (ASHRAE 1989). Temperatures above 60^0C are especially effective. In addition, evaporation shows a linear relationship with surface area available for evaporation.

It follows that a more effective evaporator will have four elements:

- high energy input rate,
- low thermal mass so it heats quickly,
- large surface area,
- be resistant to clogging by residual salts.

A transparent top on the evaporator tanks, with a reflector on the back wall, allowing solar radiation to directly heat the liquid, would satisfy the first element.

A shallow tray within the existing evaporator tank would fit the requirements for low thermal mass and would be non-clogging. Surface area would be almost double that of the existing evaporator, but less than would be possible with matting (matting would have a higher surface area, but would clog more readily).

The tray, if supported just below the pipe bringing liquid from the liquid storage tank, will be continually topped up (see figure 3.21). Excess liquid will overflow the sides of the tray and be stored in the bottom of the evaporator tank.

The tray will fit in the existing evaporator as follows:

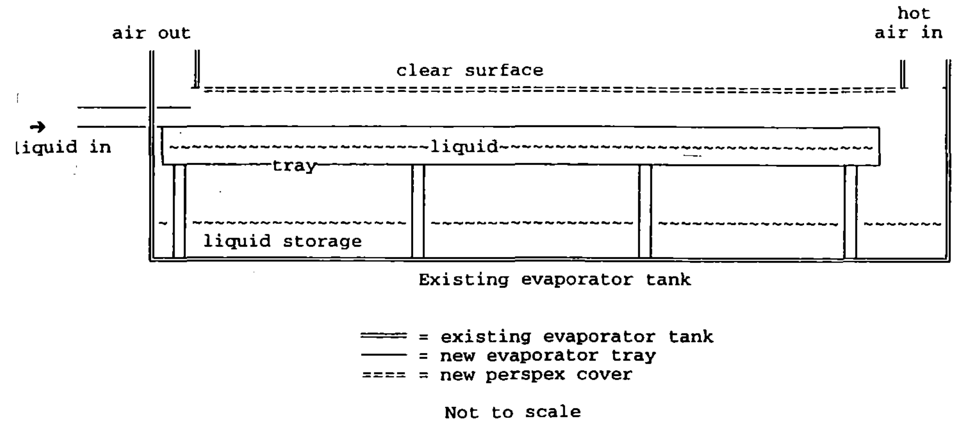


Figure 3.21 The evaporator tray and how it will fit in the existing evaporator.

3.9.4 Results

The performance of the installed tray was assessed over two days (one hot day and one cloudy) 6-7/12/92 and can be seen in figure 3.22. The fan was operating. The humidity sensors were again giving false readings so a full energy balance could not be carried out and evaporation rate is not known. Tray temperatures reached 40^{0}C (this was lower than expected). Some of the difference between expected and actual performance can be explained.

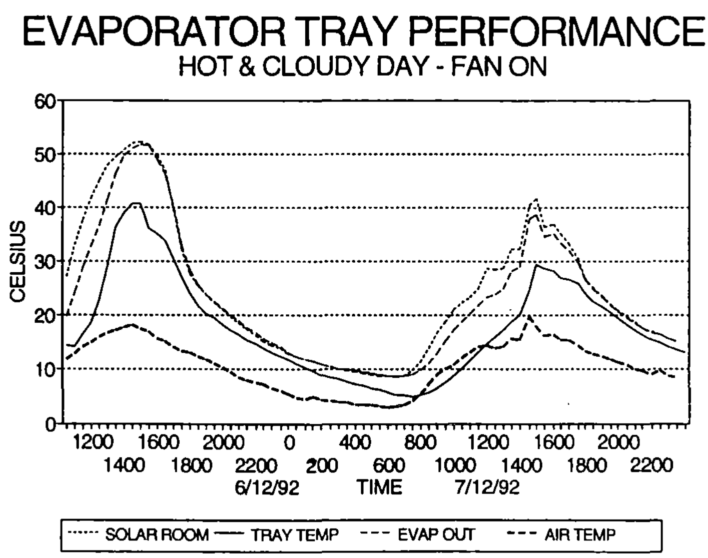


Figure 3.22

1/ The tank was adjacent to the easterly wall of the solar room and did not receive direct solar radiation until late morning. Figure 3.22 shows that warming of the tray did not start until 1130 hours, and maximum tray temperature occurred at 1430 hours. This suggests that if the solar room was designed to allow sunlight to fall on the evaporator tank earlier (by having a transparent eastern wall), extra hours of higher evaporation would have occurred and the tray temperature may have been closer to expected temperatures.

2/ The solar room and evaporator exit air temperatures were both 10^{0}C higher than tray temperature, which would suggest it was increased evaporation, due to the higher air flow with the fan on, that has cooled the tray.

3/ The design augmented solar radiation with a reflector on the back wall. The old evaporator tank tops were too large to fit out the door and being weathered stainless steel, were fitted to the wall as reflectors. They would not be as effective as polished metal.

The evaporator was inspected at the end of January, three months after they were installed. The tanks, which had been dry when the trays were installed, had accumulated some liquid indicating that evaporation is still below liquid supply. Further improvements will require structural changes to the building so it would be better to dispose of surplus liquid through a properly constructed facility.

Some design faults had become apparent:

- The perspex top on the tanks had sagged between supports (the heat of the evaporator had softened the material). In addition perspex was difficult to attach to the top of the tanks; screw holes produced stress fractures and the side of the tanks were often inaccessible to screws (due to the proximity of the surrounding building) eliminating the possibility of using angle brackets. Other material with more structural strength and more tolerant of drill holes (such as twin walled carbolux) would be more appropriate.

- The tube draining excess liquid from the liquid storage tank is only 15mm polythene. In the past these have blocked at the storage tank end, with a white scum that floats on the surface of the liquid storage tanks. With increased evaporation and increased condensation, the flow of liquid through this pipe is increased and further blockages are likely. A T-join fitted on the liquid storage end of the pipe, so liquid just below the surface is removed, would fix the problem but would require removal of the compost tanks. Removal and refitting of the compost tanks is a major task.

3.10 DISCUSSION

This analysis has given valuable insight into heat movements within the toilet. It has provided little understanding of the composting process, however this is investigated in chapter 4.

3.10.1 Evaporation

The current design suffers from trying to do two jobs at once (evaporation and heating). Water is being condensed in the compost chamber and this conflicts with the goal of evaporation of all liquids. If the liquid storage/compost carousel were modified so that any condensation is drained away as clean water, then both increased heat transfer and increased evaporation could be achieved with the same air. To achieve this, an efficient evaporator, and some design changes to ensure separation of faeces and condensed water, would be required. Bacteria may grow and survive in the condensed liquid, but it can be assumed that any pathogen which is unable to grow outside the human body, will not be present, unless direct contamination has occurred. Organisms included in this category will be viruses, helminths and higher organisms such as giardia. Ironically these are the organisms most difficult to remove with conventional water treatment systems.

Even if condensation were drained away, it may be better to separate the two tasks and have a dedicated evaporator and a dedicated heat collection system.

Liquid storage is designed to store heat from warm days and release it during cold days. This objective is compromised by the liquid being in contact with the air that enters the compost chamber. Higher temperatures in the liquid increase evaporation and any surplus heat is quickly removed as latent heat in the evaporated water. In effect, the design ensures the compost room will remain close to ambient temperature. The objective (heat storage for non-sunny days), would be better realised if the liquid in the liquid storage tank were kept separate from the airflow system.

The evaporator tray has improved the evaporative performance of the toilet, but this is still below the rate required for complete evaporation of all liquids. Any further improvement would require structural modifications to the solar room. However there is another option.

Urine provides most of the liquid produced from the toilet. Urine contains far fewer pathogens than faeces; many of the water-borne pathogens likely to be of concern, such as giardia, and worms (helminths) are not present in urine. It could be collected separately and discharged into the forest litter through a small treatment process (wetland), with very little risk of contamination. This would reduce the quantity of liquid to be evaporated and assist the composting process by reducing the moisture content of the composting mass (The moisture content of the poorly decomposed Soltran compost was 75.6%, and Enferadi (1981) found moisture contents up to 80%. The upper limit for composting is 65%-70% - see chapter 4 for further discussion).

3.10.2 Ventilation and heat transfer

Very little heat is transferred and what is transferred is quickly lost from storage. With the compost likely to produce only 30 watts, it would be difficult to achieve a warm compost room with the heat transfer system available. Heat losses from evaporation have been discussed above, however the large surface area of the walls surrounding the carousels increase conduction losses. In addition, the compost room is of timber frame construction, making it difficult to seal, better materials are available e.g. freezer panels. The compost carousel would be a better location to have the insulation, the surface area would be minimised and it would be easy to seal. A fibreglass blanket was wrapped around the carousels, but temperatures still remained low; indicating the low heat transfer rates. The requirement for warmth in the composting process is assessed in chapter 4.

Very little air is required for composting (see chapter 4), and what is required should preferably be warm and moist. The fans that were installed, have been a waste of time and money. Their shafts are composed of steel, and rust in the corrosive environment resulting in excessive maintenance. In addition, they have had very little effect on evaporation and have probably hindered composting. If the evaporation system were separate from compost aeration, or urine was kept separate and discharged, there would be no requirement for assisted ventilation, other than to keep odours out of the toilet cubicle. In this respect the fans were no better than solar assisted ventilation, as they were powered by solar panel and only turned on when the solar room was warm. Thus the problem of smell in the cubicle in the early morning still remained.

3.10.3 Preventing airflow at night

The original design used an automatic, heat operated air vent control to stop the airflow when the solar room was cool. The vent was located where external air entered the solar room (location 0 - figure 3.1). It was ineffective in two aspects: first, airflow still occurred even when the vent was closed and second, it was slow to react. The slow reaction time meant that the door was not opening until late morning when the solar room was quite hot, hence reducing heat transfer. The difficulty in sealing an entire room meant airflow continued even when the vent was closed. A better location, to stop airflow, would be the evaporator air input ducts.

The benefit of preventing airflow at night can be assessed from the data. The energy balance can be separated into night-time and daytime, and the loss of heat from the compost room can be compared to the effect on total evaporation (figure 3.23 and 3.24). Daytime was taken between 900 and 1800 hours, thus there were 9 hours of daytime and 15 hours of night-time. Figure 3.24 shows approximately half of the net water evaporated on a hot day is evaporated at night while, for cold days the night-time evaporation rate exceeds the daytime (because of the number of hours in night-time rather than a higher evaporation rate).

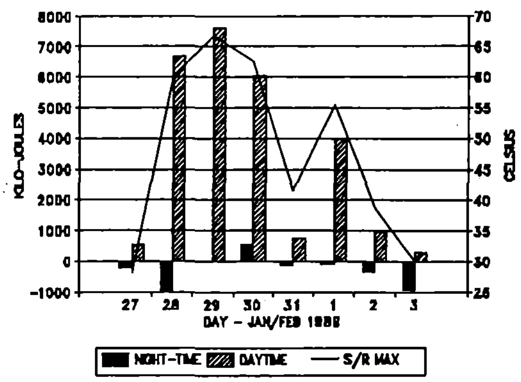


Figure 3.23 Heating of the compost room proportioned between night-time and day time contributions.

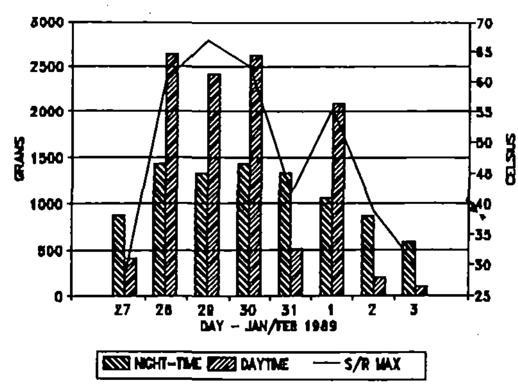


Figure 3.24 Net water evaporation proportioned between night-time and day time evaporation.

Heating of the compost room (figure 3.23) shows relatively little heat is removed at night. This is partly due to the reduced airflow that occurs as the solar assisted exhaust cools, but also due to storage of daytime heat in the solar room. It is only after midnight that there is net removal of heat from the compost room by the ventilation air (figure 3.15), except after a cold day when net removal becomes negative after 1800 hours (figure 3.16).

This analysis shows that allowing air to flow all the time, will greatly benefit evaporation but will have little effect on heat removal. This is also evidence that the evaporation system should be separate from the compost heating system. Only then would it be possible to retain the benefits of evaporation at night and prevent removal of heat from the compost room. Note however, that this analysis only applies to the toilet with existing heat flows. If more heat were stored in the compost room, by either auxiliary heating or better heat transfer from solar sources, then greater losses due to ventilation air would occur.

3.10.4 Overload

The toilet, in its current form, appears to be overloaded, although it is operating within its design loading rate.

There is some evidence to suggest a management strategy that uses a chamber and then allows a period for composting, may allow satisfactory composting to occur with high use rates. The results of the trials, discussed in chapter 4, allow quantification of the optimum use/rest periods for composting.

Support for this claim arises from two sequential years of operation of the Soltran. Generally the carousels were rotated twice in a season, each loading lasting for approximately one month. During the 1990/91 season, in response to concerns that fresh additions on top of the old compost would be contaminating the old compost, each carousel was rotated once. Each chamber thus received two months of additions, and was then left to compost for the rest of the year. The worst compost ever dug out of the Soltran, came from this season. The staff were not at fault, in fact they were especially diligent and sympathetic to composting toilets. In response to this, the following year the carousels were rotated every 3 weeks and then given 9 weeks to compost before receiving more contributions. This regime produced good compost. It would appear that a rest between successive additions is desirable. Chapter 4 establishes that the rest period between successive additions should be influenced by the temperature of the compost.

CHAPTER 4

LABORATORY SCALE COMPOSTING TRIALS

4.1 OBJECTIVE

The objective of the laboratory scale trials, was to find factors that both improve compost quality, and that can be manipulated in the field. The questions asked by field staff were:

- what type and how much bulking material?
- how important is mixing?
- what happens in cold conditions?

Monitoring of the Soltran enabled the evaporation problem and heat transfer characteristics to be assessed. The Soltran data did not help to identify the problems in the composting process. This was best done with controlled experimental conditions.

Compost toilets operate with high airflow around the compost, to remove any odours. It was felt that this situation could be simulated, in the trial situation, by placing porous reactors in a controlled environment room. Trials done at different room temperature settings would test:

(a) whether there is a threshold ambient temperature for composting (>37^0C was alluded to by the manufacturers).

(b) whether composting could proceed in cooler winter temperatures.

The initial trial was set up with small, porous reactors in a room at a set temperature of 40^0C i.e. very warm. Compost temperature rose only a few degrees above ambient temperature, but there were large water losses. A simple calculation indicated that the energy required to evaporate the water would remove all surplus heat and leave none to warm the pile.

Therefore an experimental set up that controlled ventilation was essential.

4.2 METHOD

Reactors have been used to simulate conditions within large compost piles (Ashbolt and Line, 1982; Bagstam *et al.*, 1974; Campbell *et al.*, 1990a, 1990b; Deschamps, *et al.*, 1979; Jeris and Regan, 1973a; Mote and Griffis, 1979, 1982; Schulze, 1962; Sikora *et al.*, 1983; Suler and Finstein, 1977). These designs were assessed as to whether they would adequately simulate the conditions within the small pile of a compost toilet. Therefore the question was, what are the differences between a large compost heap and a small one?

Two differences are: first, all compost is close to an edge, so air can diffuse into, and water evaporate from, a small compost pile, and second, a small pile does not receive significant heat from the surrounding compost (conduction dominates heat loss).

The reactor design chosen, consisted of 21 litres of compost in a plastic mesh container placed inside a 64 litre plastic drum (figure 4.1). This meant the compost would be surrounded by air, allowing oxygen to diffuse into the composting pile. The reactors were located in a room in which air temperature and humidity could be controlled. They operated as a self-heating, batch loading system. The design enabled accurate heat production calculations to be made on an hourly basis.

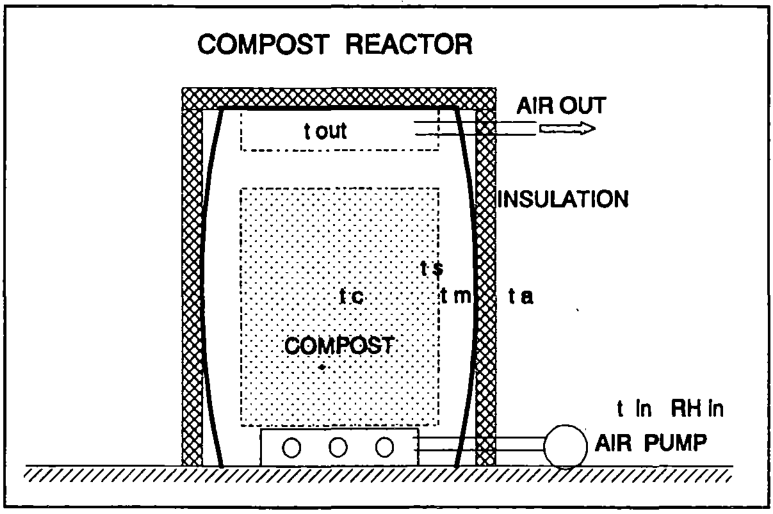


Figure 4.1 Cross section of the compost reactors

Heat lost by conduction was calculated by temperature difference between t_m and t_a (see figure 4.1 for sensor location). Calibration of the reactors was carried out using a 12 volt, 30 watt resistor suspended in the middle of the reactor. The system was allowed to equilibrate (24 hrs) with no airflow and the temperature difference noted. The value of UA (conductance * area) was calculated for each reactor. There was a difference in the UA value between the reactors because there were higher airflow areas produced by the air circulation in the room. See appendix 1 for details of the reactor energy balance.

4.2.1 Trial set up

Pig faeces were used in the trials instead of human faeces because of problems of supply with human faeces (see section 2.9.1). A trial comparing human and pig faeces showed similar heat production profiles between the two (see section 4.4). The pig faeces were collected from the floor of a pig house immediately before a trial was commenced. The feed for the pigs was controlled, with the proportion of each ingredient weighed. Young pigs were feed more protein than older pigs but the pens were interspersed, hence each bucket of faeces collected would contain a mixture from old and young pigs. Variation in the faeces, between and within runs would be minimised.

There was some variation in the temperature of the mixed compost at the start of the trial. This was mainly due to weather conditions during mixing (mixing was done outside), and produced more variation between trials than within each trial. This temperature variation was of concern in the cold temperature trials but had little effect in the warm temperature trials.

At trial 8, the source of bulking material was changed from shavings and sawdust from the university's carpentry shop, to another source of sawdust. This sawdust was finer than the carpentry shop bulking material, tended to yield higher temperatures and higher watts, and was more consistent in performance. Thus, where there was a surplus of trials to that required for statistical analysis the earliest trials were deleted.

4.2.2 Data collection and analysis

18 trials were done, each lasting for 2 weeks, although one trial was left for one month. The first trials were used to understand the system, changing insulation, etc. Airflow remained constant for the duration of the trial, and was set for each reactor using a 'Platon' gapmeter. Optimum airflow was established by trial 6.

The data was collected with a Campbell CR10 data logger, from AD590 temperature sensors and, 'Automation engineering' humidity transducers. The data was collected every hour but the spreadsheets and resulting calculations were excessively large. The Campbell split programme was used to obtain 4 hour averages. The resulting graphs were smoother than the 1 hour average and there was very little loss of detail.

An energy balance approach was used to calculate the watts produced by the compost. Temperature sensors were sited to assess conduction losses and temperature and humidity sensors allowed ventilation losses to be measured. Details can be seen in appendix 1.

Heat output was the main parameter assessed as it was felt that if heat output could be maximised then pile temperatures would be higher and composting proceed faster.

Data was used in two ways:

1. A time series plot of the various parameters allowed visual comparison of treatment effects within each run.

2. Extraction of critical data (e.g. maximum temperature) for each run allowed comparisons, and statistical analysis, to be made between runs.

A two-sided t test was used to assess statistical significance.

4.3 RESULTS

4.3.1 Heat losses from a compost pile

Heat losses occur in two ways:

-ventilation losses (vapour and hot air)

-conduction losses

Figure 4.2 shows these losses diagrammatically.

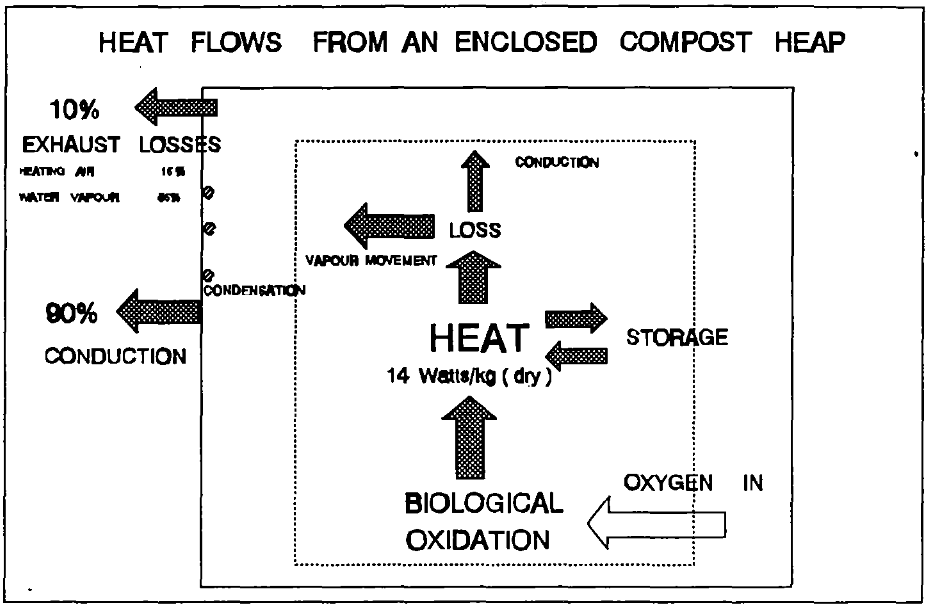


Figure 4.2

Figure 4.3 shows the proportion of heat that was lost by ventilation.

For the optimum airflow (300 cm^3/min.kg(dry)), 9% of the heat was removed by ventilation, this dropped to 4% when the room temperature was lowered to 4^0C.

The total energy lost over the duration of the trial, was used to assess the proportion above.

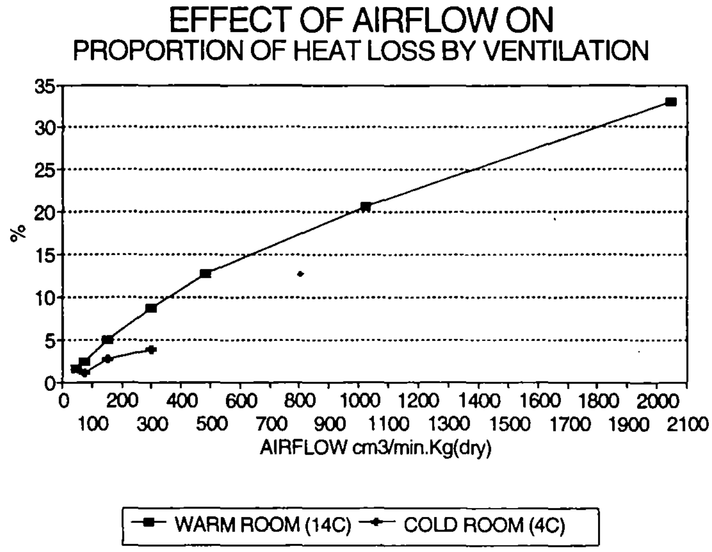


Figure 4.3

There was however, some variation in the proportion lost by ventilation as the trial cooled. The time series data for trial 14, reactor 2 show the changes over time (figure 4.4).

Ventilation losses rise from 0 to 5 Watts as pile temperature warms but the proportion changes little (10% to 13%) while the pile is hot. Ventilation losses rose to 20% as the pile cooled.

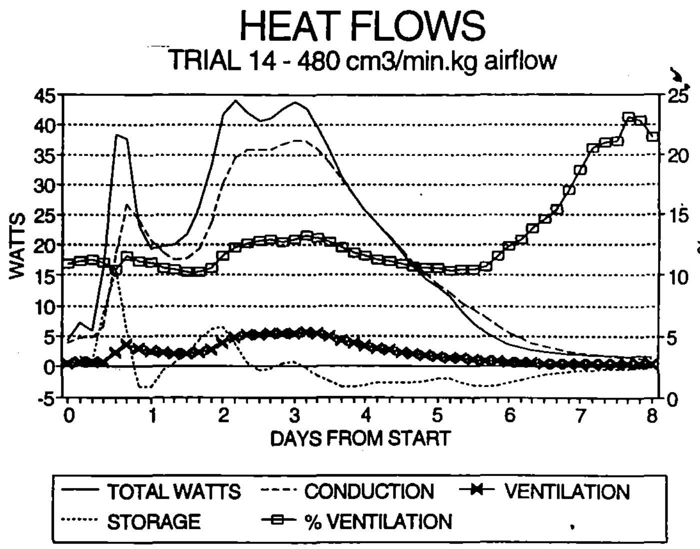


Figure 4.4

4.3.2 Water movement within a compost pile

Water, that is lost from the pile appears as either, water vapour in the exhaust air (ventilation loss), or liquid in the bottom of the reactor. The liquid in the bottom of the reactor can come from two sources; vapour condensation on the walls of the reactor and drainage from the bottom of the pile.

4.3.2.1 Water loss by ventilation

Figure 4.5 shows the proportion of water that is lost by ventilation. At optimum airflow (300 cm^3/min.kg(dry)) it is just under 20%. At some flow-rate (higher than used in these trials), the air conditions in the reactor will approach those of the room

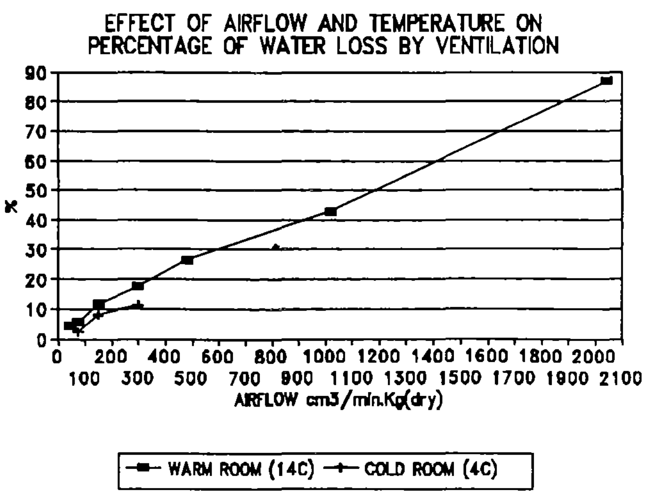


Figure 4.5

air (i.e. will be the same as conditions in the initial trial, where the compost was not surrounded by an impervious container, and the room air could freely circulate around the compost).

4.3.2.2 Water loss by condensation and drainage

Vapour condensation and drainage end up at the same location (in the bottom of the reactor). The amount of water from the reactor that was condensate, as distinct from the amount that was drainage, was measured in two ways:

1/ A heavy plastic bag was placed under the compost so that drainage from the bottom of the compost would drain into the bag and could then be measured separately from the rest of the reactor water. This was done on 2 occasions, trial 3 gave 4.7% from drainage and trial 4 gave 5.2%.

2/ Later a collector lip was installed inside one reactor, 110 mm from the bottom of the reactor. Condensed water collected by this lip was drained, via a plastic tube, to a container outside the reactor. The location of the lip meant that some condensation, i.e. that vapour condensing on the part of the reactor case that was below the lip, would appear as drainage from the compost. Thus this method would over-estimate the drainage component.

Using this method, the amount of the reactor liquid that was drainage was 13% in the warm room but dropped to 8% in the cold room. Whichever measurement is used, *there is considerably more liquid*

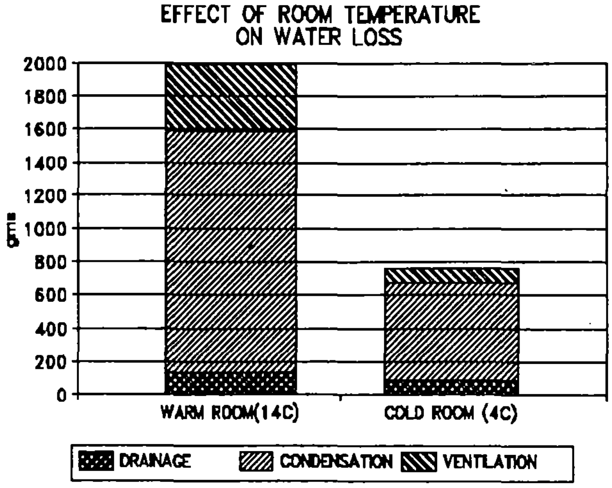


Figure 4.6

condensed on the side of the reactor than drains out of the bottom of the compost (figure 4.6).

4.3.3 Moisture content changes

Raw pig faeces have a moisture content of 77% (wet mass); mixing with sawdust reduced the overall moisture content to 62±3%. Thus composting was occurring near the upper limit of acceptable moisture content. At the conclusion of each trial the compost was noticeably damp on the surface and dry in the middle, so a moisture content sample was taken from the top (edge), and middle, of each reactor at the finish of each trial.

The moisture content changes are shown in figure 4.7. Less drying occurred in the middle of the pile in the cool room, as the pile temperatures are lower and enthalpy (the driving force for heat and mass transfer) is much lower.

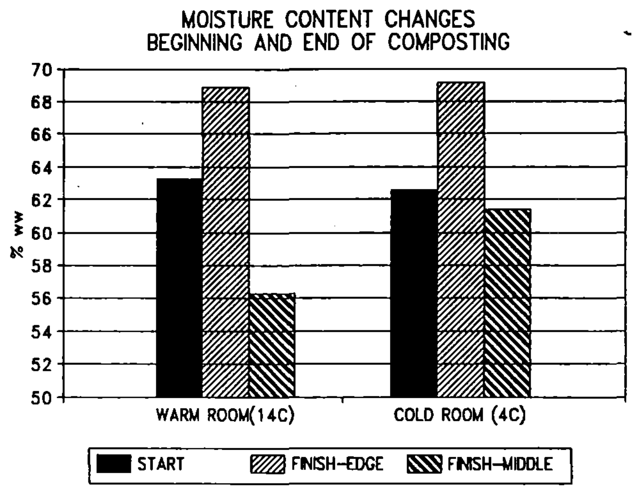


Figure 4.7

It was not established whether moisture content changed linearly between the two measurements. Observation suggested that there was a moist surface (extending inwards about 20 mm).

4.3.4 Organic matter oxidation

Three methods were used to assess organic matter oxidised.

A/ A moisture balance was achieved by subtraction of dry mass at the end of composting from dry weight at start, the difference represented the amount of organic matter oxidised.

Because of the variation in the moisture content within the pile at the end of composting, the moisture content of the middle and edge were averaged for the calculation.

B/ A mass balance was achieved by subtracting wet mass of the compost at the end, from wet mass at the beginning. The loss of mass is either: water i.e. liquid from reactor container and moist air losses, or organic matter burnt off to gasses (CO2, NH3 and water). Reactor liquid was measured, and moist air losses were calculated. The actual loss of organic matter will be underestimated by this method as the water resulting from organic matter oxidation will be measured in the exhaust gasses. This method gave results around 2%-6% DW oxidised, while moisture balance and ash analysis gave values in the order of 18% DW oxidised. Mass balance data were more accurate at high air flow settings (see figure 4.16). The results from the mass balance calculations were disregarded.

C/ Ash analysis was begun later in the series to verify the other methods and for comparison with other published data (see appendix 2). However the ash analysis data was very variable (see figure 4.8). Two reasons can be advanced to account for this variation:

(1) experimental: such as, absorption of water by the samples before weighing for ashing, and incomplete combustion in the furnace.

(2) sample variation: i.e. the ash content of sawdust is much lower than faeces (1% versus 20% (Szpadt, 1990; Lentner, 1981). The distribution of bulking material varied greatly in some of the reactors (especially the poorly mixed and leaves reactors) and this variation influenced the percentage of ash in the samples.

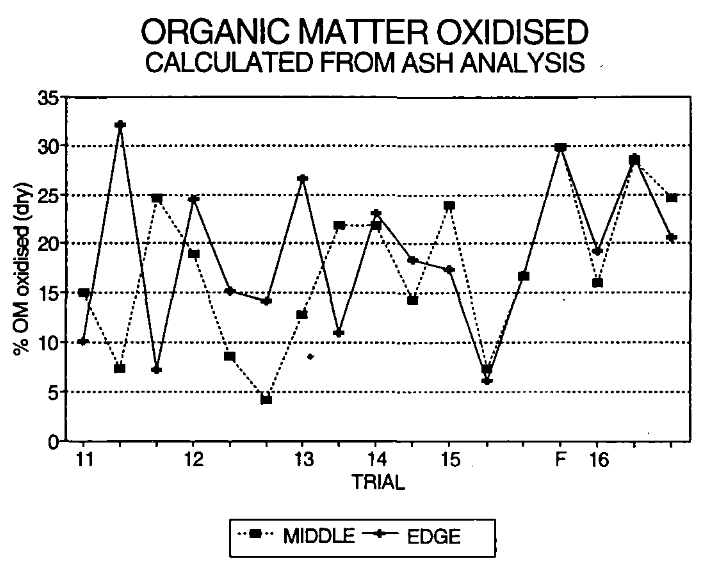


Figure 4.8

Error in the ash content is magnified in the calculations of organic matter oxidised. Greater accuracy could be achieved by replicating the samples, and/or using a bulking material that had an ash content closer to that of faeces.

The data, although variable, give useful indications of processes in the compost pile not able to be obtained by other methods.

Ash analysis indicates more organic matter is oxidised in the edge of the pile than in the middle (figure 4.9). The average for all trials was, 18.9% oxidised in the edge and 17.4% oxidised in the middle. This is counter to what was expected, as the middle of the pile is warmer and this should have given better breakdown. The most likely explanation is the availability of oxygen. This is supported by the fact that of the 7 reactors (out of 17) which showed more organic matter oxidised in the middle than the edge. Two of the seven were high air flow reactors (more oxygen available), two were from the cold room trials (pile temperatures were lower and rate of oxygen consumption in the edge layer less) and three were in the warm room, but had low pile temperature: one due to poor mixing and two were only half filled reactors (with less distance to the middle and consequently better air access). Thus a reason can be advanced to explain all of the anomalies to the trend of greater oxidation in the outer layer of the compost.

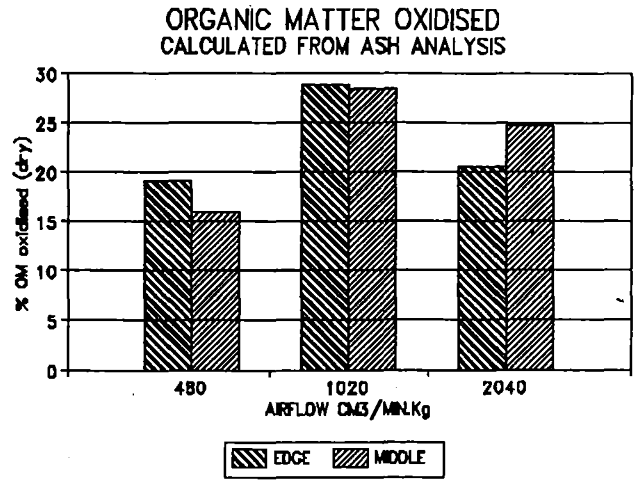


Figure 4.9

The organic matter oxidised, as calculated above, uses the dry weight of both faeces and bulking material. It is known that sawdust is largely unavailable to composting micro-organisms; therefore almost all of the organic matter oxidised will be of faecal origin. We can adjust the values recorded to acknowledge this fact. On a dry mass basis there is a similar quantity of faeces to sawdust (1.5 kg(dry) each), therefore the values of organic matter oxidised can be doubled to give a value for faeces composted. Thus 36% of the faeces will be oxidised and 0% of the sawdust will be oxidised. Compare this with the leaves bulking material, where organic matter oxidised is 30% of both leaves and faeces. Clearly part of the leaf is being used by the compost micro-organisms.

Verification of the 36% figure can be obtained indirectly from the literature. Haug and Ellsworth (1991) measured the degradability of sewage sludge at 46% volatile solids, and Lentner measured ash content of human faeces at 20% (volatile solids = 80%). Thus 46% of 80% is 37% of total organic matter degraded. This amount of degradability is at the lower end of values expected for water based treatment systems, however composting is still occurring, albeit at a low rate, at the end of composting (see section 4.3.9).

4.3.5 Effect of room temperature on the composting process

Figures 4.10 and 4.11 show the effect of room temperature on the composting process

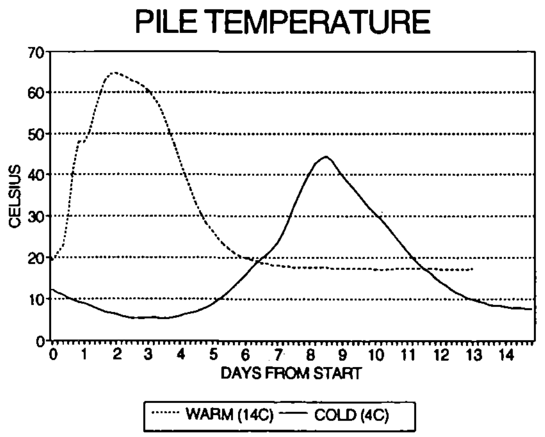


Figure 4.10

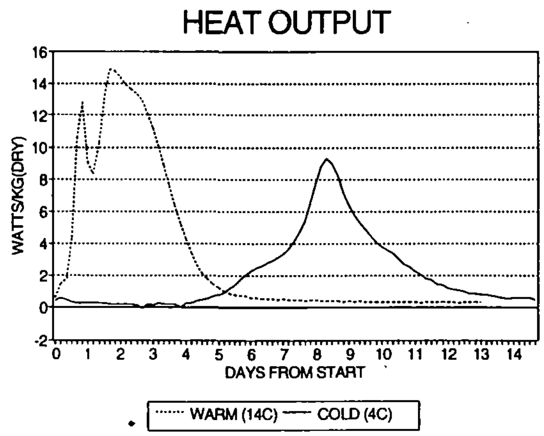


Figure 4.11

Lowering the room temperature had an impact on all critical data measured; most were highly significant differences.

TEMPERATURE DATA	Hot room 14°C	Cold room 4°C	Change from hot %	Probability P	significance
Maximum temperature	61.5	43.7	-28.9	.031	*
12 day average temperature	31.9	16.8	-47.3	.0014	**
Maximum temperature above ambient	45.8	38.9	-15.1	.21	ns

Table 4.1 The effect of room temperature on compost temperature.

ns = not significant

* = significant

** = highly significant

Table 4.1 shows the temperature of the cold room was 10^0C below the warm room temperature. The maximum and average temperatures of the compost, show a drop greater than 10^0C. While the temperature above ambient decreases with cooler temperatures, the drop is not significant.

PHYSICAL DATA	Hot room 14°C	Cold room 4°C	Change from hot %	Probability P	significance
Weight loss of the compost (%ww)	26	8.9	-65.8	.012	**
Organic matter oxidised:-moisture balance (% dw)	15.7	13.3	-15.3	.76	ns
Time to initiation (days)	.4	4.3	975.0	.14	*

Table 4.2 The effect of room temperature on physical data.

The highly significant effect, of cold room temperatures, on wet weight loss (table 4.2) is of concern for compost toilets. The effect was mostly confined to water losses as there was less effect on organic matter oxidised (not significant). The time to initiation was also significantly affected.

WATER DATA	Hot room 14 °C	Cold room 4 °C	Change from hot %	Probability P	significance
Water evaporated (gms)	402.1	85.3	-78.8	.0045	**
water condensed in the reactors (gms)	1671	692.3	-58.6	.025	**
Moisture content changes - middle (change in %age points)	-7	-1.2	-82.9	.11	ns
Moisture content changes - edge (change in %age points)	5.6	6.5	16.1	.71	ns

Table 4.3 The effect of room temperature on water data.

Of particular concern to compost toilets operating in a cold environment are the effects on water removal (table 4.3). There is a 79% decrease in the amount evaporated and a 57% decrease in the amount condensed. The evaporation effect is due to the decreased ability of the cooler exit air to hold water. The condensation effect is harder to explain but is probably due to the decreased driving force (enthalpy) of the cooler compost pile.

ENERGY DATA	Hot room 14°C	Cold room 4°C	Change from hot %	P	significance
Maximum watts	14.7	10.1	-31.3	.059	*
12 day average watts	4.1	2.4	-41.5	.014	**
Total Energy (kJ)	13674	9446	-30.9	.0075	**
Energy lost by conduction (kJ)	12483	9148	-26.7	.015	**
Energy lost by ventilation (kJ)	1249	349	-72.1	.0046	**
Energy in the water condensed in the reactor (J)	3453	1431	-58.6	.025	**
Condensation J / conduction J (%)	27.7	15.7	-43.3	.017	**

Table 4.4 The effect of room temperature on energy production.

The drop in maximum Watts (table 4.4) is due to the reaction rate effect of temperature on biological reactions. This will be discussed later. The drop in the rate of heat output reduced the maximum temperature that the pile reached above ambient.

All of these impacts of cold temperature, have major considerations from a design point of view, especially the effects on water removal if a design aim is zero discharge of liquids.

4.3.6 Effect of airflow

The effects of airflow on heat loss and water loss are mentioned above. Airflow had different impacts between maximum and average values of the critical data.

Three areas can be identified from figures 4.12 to 4.15: up to 150 cm^3/min.kg(dry), 150-300 cm^3/min.kg(dry), 300-2000cm^3/min.kg(dry). No trials were done at airflow rates above 2000 cm^3/kg(dry)

1/ Up to 150 cm^3/min.kg(dry)

This stage is dominated by increasing heat output of mesophilic micro-organisms responding to increasing availability of oxygen.
All temperature measurements (maximum and average), continue to rise with increasing airflow, while the amount of organic matter oxidised, declines by a few percentage points.

2/ 150 - 300 cm^3/min.kg(dry)

This stage is dominated by the effects of thermally induced inhibition of the microbial population. The maximum temperature continues to rise, with air flow, to the highest recorded temperature of 64 ^{0}C. On the basis of maximum temperature this would seem to be the optimum airflow, however on all other parameters this is the worst airflow.

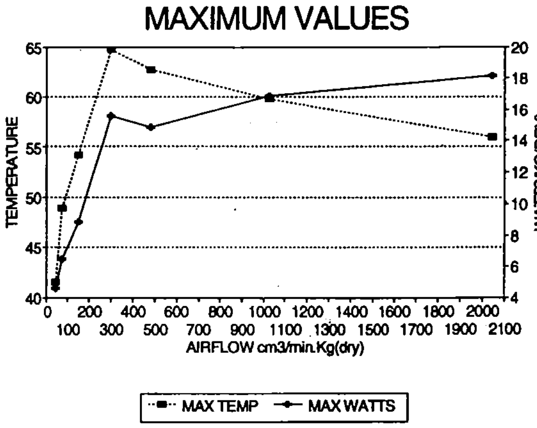


Figure 4.12

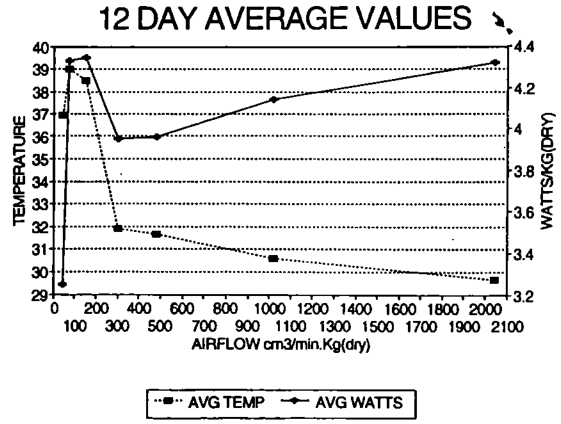


Figure 4.13

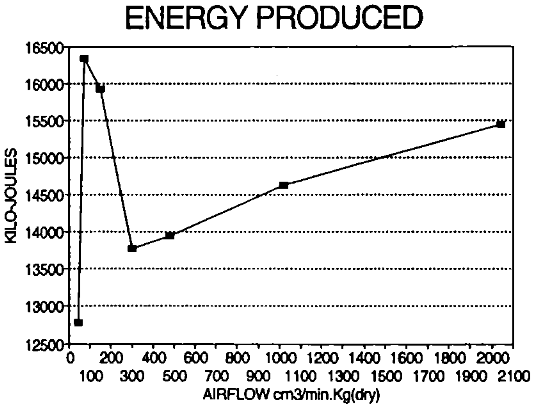


Figure 4.14

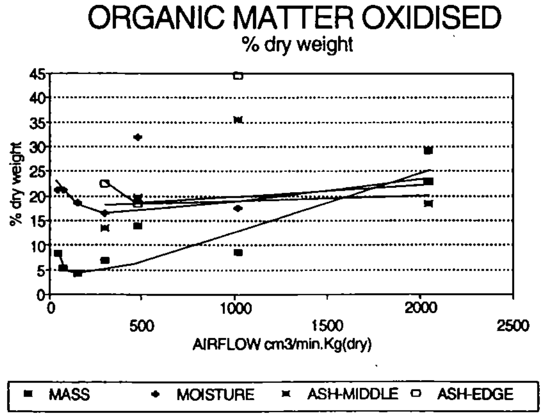


Figure 4.15

Both the 12 day average temperature and average Watts decline rapidly, in the case of Watts, to a minimum value for the airflows tried (with the exception of the very restricted airflow)

The amount of energy produced in total, declines to a minimum; as does the amount of organic matter oxidised.

Plotting average Watts against maximum temperature (figure 4.16), indicates that the effect of thermally induced inhibition begins to occur at 54^0C and appears to be linear up to 65^0C.

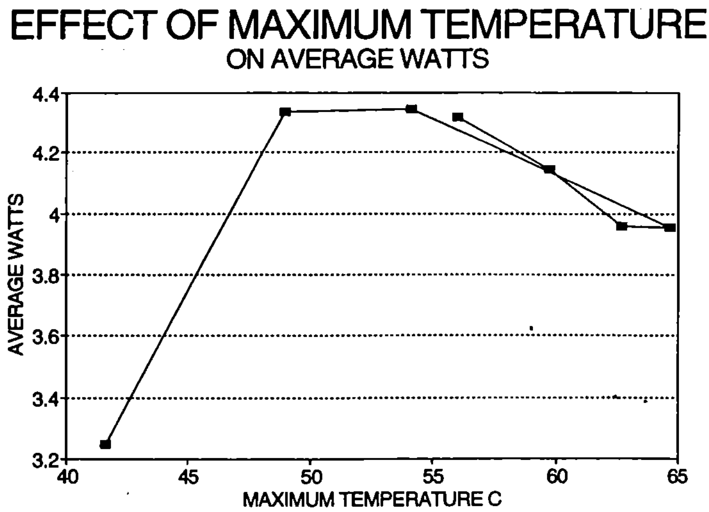


Figure 4.16

This result agrees with McKinley *et al.* (1985b).

3/ 300-2000 cm^3/min.kg(dry)

The effects of thermally induced inhibition become less with increasing airflow in this stage. Both maximum and average temperature decline, as ventilation losses increase. This decrease in maximum temperature appears to be enough to allow the microbes some degree of stability, as despite the decrease in average temperature, the rate of heat output (Watts) continues to rise (the reaction rate constant for microbial activity would predict a *decrease* in Watts produced with decrease in temperature). This increase in average Watts is reflected in the organic matter oxidised, which continues to rise.

The effects of airflow on the composting process noted above, must be taken in the context of the room temperature and reactor size used. Higher airflow influences maximum temperature only because of the increase in evaporative cooling (heat removal), and it is maximum temperature that impacts on microbial activity. A different result would be expected if it were other factors (eg cooler room, less insulation, or less organic matter to oxidise), that held temperatures below the point where thermally induced inhibition occurred (54^0C). One would expect that the drop in the average Watts between 150 and 300 $cm^3/kg(dry)$, would not be noticed if room temperatures were lowered so that the maximum temperature did not get above 55^0C. The cold room data cannot be used to assess this effect as compost temperatures only just reached thermophilic values. They will have suffered microbial inhibition of mesophilic micro-organisms, but would not be directly comparable to thermophilic inhibition.

4.3.7 Effect of bulking material

Four bulking materials were used. Two contained sugar supplements to sawdust and one used dried and crushed leaves from a walnut tree.

Mill effluent, from the fibreboard manufacturing plant at Rangiora was the subject of a thesis (James, 1991) so chemical composition was known. Two litres of effluent were added to sixteen litres of sawdust and then dried before use.

Grape marc has been experimentally composted (Inbar *et al.*, 1988), and was a good source of sugars. After some experimentation, the marc was oven dried and crushed, three litres of the dry marc was added to twelve litres of sawdust.

Leaves are less dense than sawdust. Thus, compost with leaves as bulking material is lighter than the other mixtures when the volume ratio for bulking material is maintained. The trial contained the same weight of pig faeces and the same volume of crushed leaves (sixteen litres).

With four bulking material types and only three reactors, data for sawdust only was brought in for comparison. This introduced an element of variation, in particular the effect of a slight difference in the temperature of the starting mix. This variation resulted in differences in time to initiation. Time to initiation had little effect in the warm room trials, but in the cold room trials it had bigger impacts.

4.3.7.1 Warm room (14^0C)

Adding sugar supplements to the sawdust extended the period that the compost remained hot. This effect was most noticeable for the dried leaves. It follows that the total amount of heat produced and the amount of organic matter oxidised was greatest for the walnut leaves and intermediate for the sugar supplements.

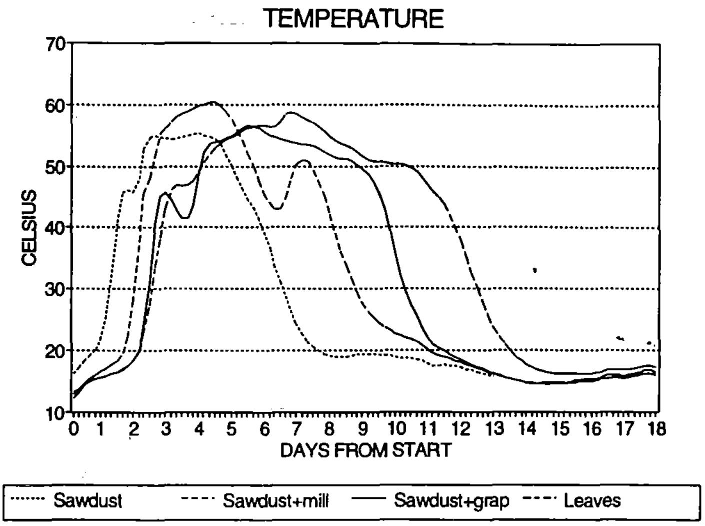


Figure 4.17 The effect of different bulking materials on the composting process - WARM ROOM

There was some variation in time to initiation, but when initiated, all piles warmed at similar rates until the mesophilic/thermophilic transition at 45^0C (figure 4.17). Beyond this point the profiles differ considerably.

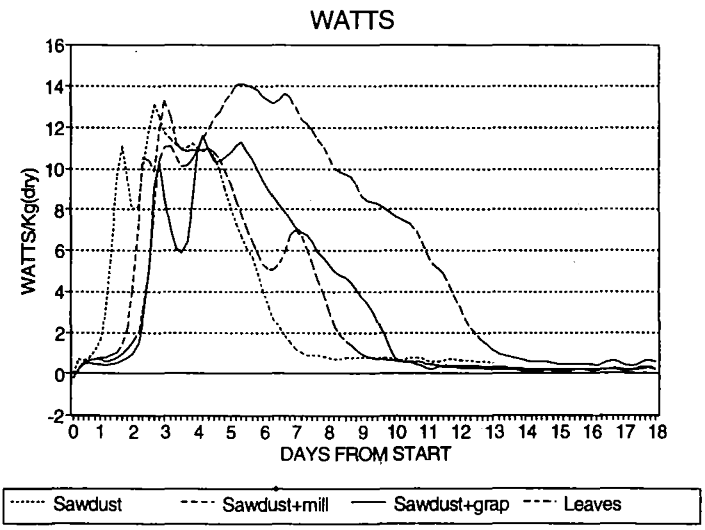


Figure 4.18 The effect of different bulking materials on the composting process - WARM ROOM

A third Watts peak is apparent in all curves (figure 4.18), but is most pronounced in the reaotors with supplementary sugars.

Leaves produced the smoothest Watts curve. This was most probably due to the greater range of substrates available from the leaves.

4.3.7.2 Cold room (4°C)

The extended hot period with supplements, that was noted in the warm room, was not so apparent in cold conditions (figure 4.19).

When initiated the piles warmed at different rates, as evidenced by the slope of the curve up to the first maximum temperature.

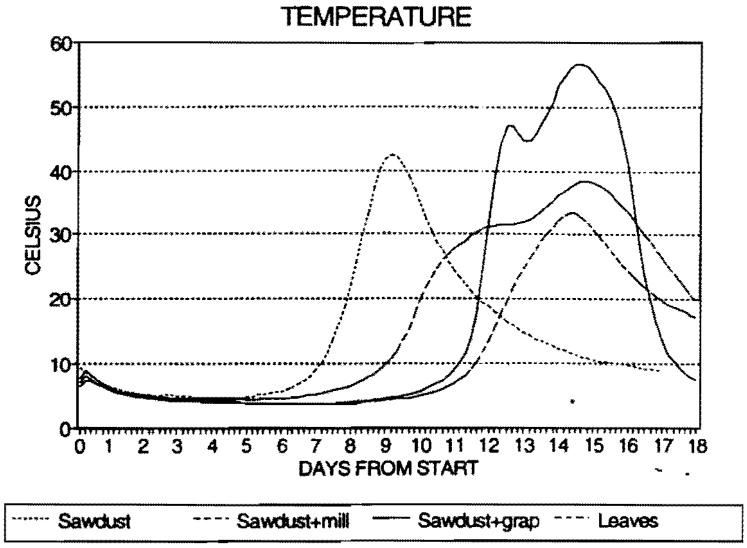


Figure 4.19 The effect of different bulking materials on the composting process - COLD ROOM

In cold conditions all Watts curves were smoother (compare: figure 4.20 with figure 4.18). The large drop in heat output, as the microbial population responds to the changing conditions, are absent.

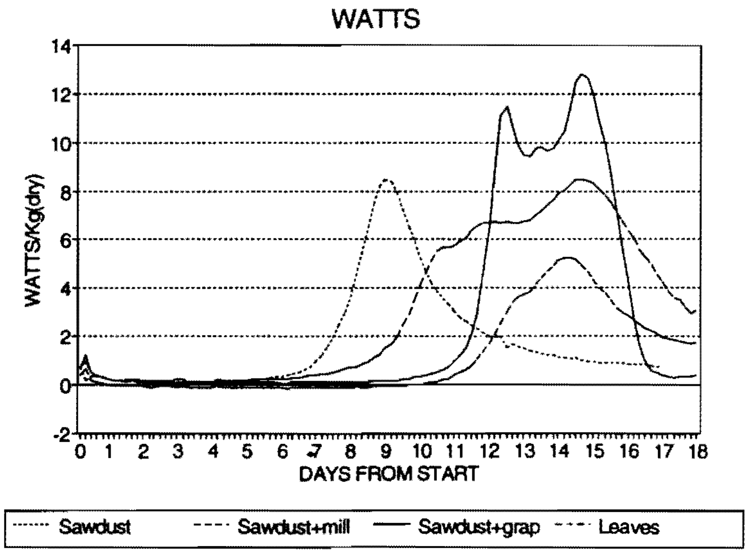


Figure 4.20 The effect of different bulking materials on the composting process - COLD ROOM

4.3.7.3 Critical factors

The extra energy available from sugar additives and walnut leaves keep the compost warmer.

for longer (figure 4.21). This extra energy is apparent in the warm room data, but is not so clear in the cool room trial for two reasons: first,the grape marc performed extremely well (achieving a heat output rate of 12.9 W/kg(dry) for a short period of time), second the earlier initiation of the sawdust reactor allowed composting to be closer to completion. The leaves were still producing 3 Watts/kg(dry), at the close of the trial, while the mill supplement was producing just under 2 Watts/kg(dry) and the remaining two (shavings and grape marc) were less than 1 Watt/kg(dry). Had the trial continued all reactors would have composted completely, and the same trends that the warm room showed would have been apparent in the cold room.

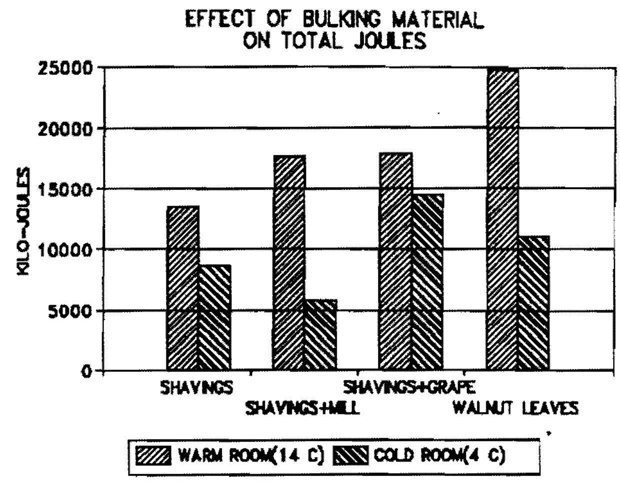


Figure 4.21

PHYSICAL DATA		SAWDUST	SAWDUST+MILL	SAWDUST+GRAPE	WALNUT LEAVES
WT LOSS %(wet weight)	-warm	26.0	29.9	33.8	39.0
	-cold	8.8	5.8	20.0	13.5
ORGANIC MATTER OXIDISED %DW (MOISTURE BALANCE)	-warm	14.1	13.2	14.7	29.7
	-cold	18.1	0.8	17.6	20.5
HEIGHT REDUCTION (%)	-warm	-	3.3	7.1	8.0
	-cold	4.0	3.4	7.9	10.0
TIME-INITIATION (days)	-warm	0.8	1.5	2.0	2.0
	-cold	6.7	11.3	11.0	8.8
DRY WEIGHT-START (gms)	-warm	2926.8	3394.8	3293.7	2574.3
	-cold	3427.1	3286.8	3617.7	2296.0

Table 4.5 The effect of room temperature on physical data

Table 4.5 shows more organic matter is oxidised with leaves, in both warm and cold rooms. This is consistent with both: the total Joules produced, and the knowledge that very little of the lignin in sawdust would decompose and supply heat. Height reduction, (the reactors were not stirred so height reduction is not the same as volume reduction) is also greatest with leaves, and reflects the loss of structural support as the leaves are composted.

The difference in the energy available in the compost also impacted on water removal (figure 4.22). The walnut leaves removed most water from the compost, while sugar additives were mid-way between sawdust and leaves. This trend is not followed in the cold room; rather, water removal closely follows total energy (see figure 4.21).

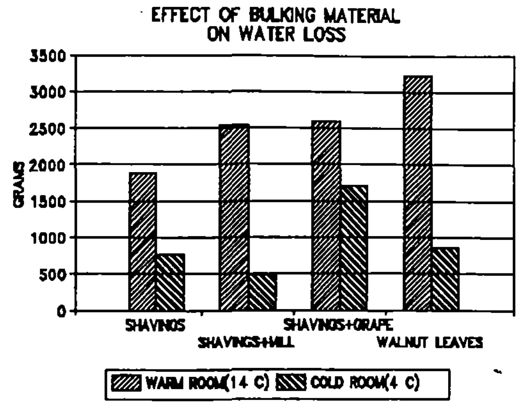


Figure 4.22

4.3.8 Effect of mixing

Three mixing regimes were used:

-'poorly' mixed was intended to simulate current conditions in the "Soltran" where bulking material is added twice a day. Large lumps of faeces (< 50 mm) are surrounded by a quantity of sawdust.

-'well' mixed aimed to have each piece of sawdust covered in faeces, with all lumps of faeces less than 5 mm in size; in effect making the bulking material surface area the biological reaction area.

-'Medium' mix was intermediate between the two.

Mixing had a major impact on the temperature profiles of the different treatments. The poorly mixed reactor remained in the mesophilic temperature range, but remained warm for a

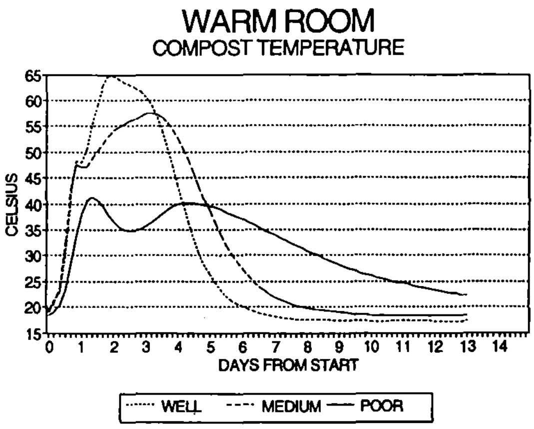


Figure 4.23

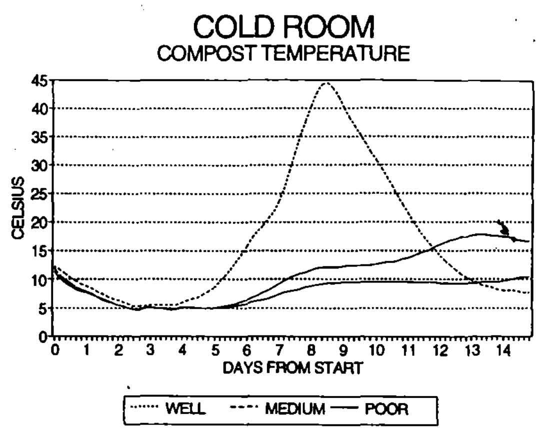


Figure 4.24

longer period of time (figure 4.23).

The differences between mixing treatments were most pronounced in the cold temperature trials, where the poorly and medium mixed reactors barely began to heat (figure 4.24).

The graph of total energy produced (figure 4.25), shows the highest value to be with the poorly mixed reactor in the warm room. This shows the effectiveness of mesophilic digestion (the poor mix did not reach thermophilic temperatures), and the effects of thermally induced microbial inhibition in the well mixed reactor.

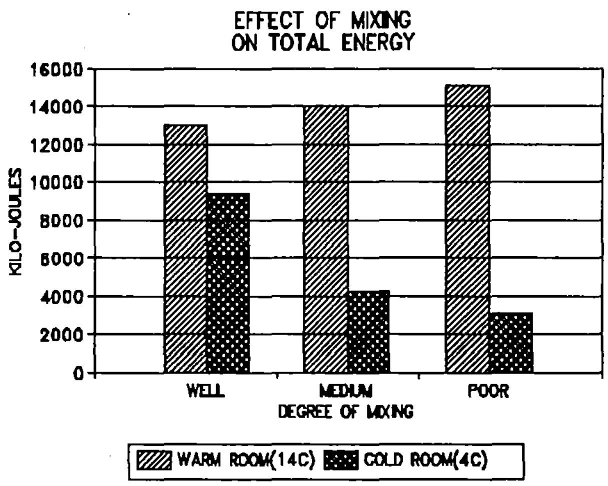


Figure 4.25

The cold temperature trials did not continue long enough to allow the medium and poorly mixed reactors to cool completely. Thus no conclusions can be drawn from the trend, in figure 4.25, for the pooly mixed reactor to release less heat than the well mixed reactor. They may have all released similar amounts of energy, eventually.

4.3.9 Residual heat production

After 14 days the reactors were still producing heat, albiet at a very low rate. It is assumed this residual heat production is microbial activity on the more refractory organics, such as lignin. The trial that was left running for 1 month, showed that there was no noticeable fall off in the rate of heat production over the two week extension.

The effect of room temperature on residual Watts can be assessed.

Room temperature (^0C)	Residual Watts (W)
4	.66
14	.42
30	1.47

Reaction rate kinetics would suggest the residual Watts would increase as room temperature increased. The anomaly, in this trend, between 4^0C and 14^0C can be explained in two ways: first, the cold room trials had only just finished composting (initiation was delayed and the rate of composting was less). Thus the residual Watts would have continued to fall with room temperature, had the trial continued. Second, the effect of heat induced microbial inhibition due to high maximum compost temperatures, impacted on residual Watts at 14^0C room temperature (figure 4.26).

The airflow used for most of the trials was 300 cm^3/kg(dry); this gave highest maximum temperature but also maximised the thermally induced microbial inhibition. The effect of the inhibition carries over to the residual Watts at the end of the trial.

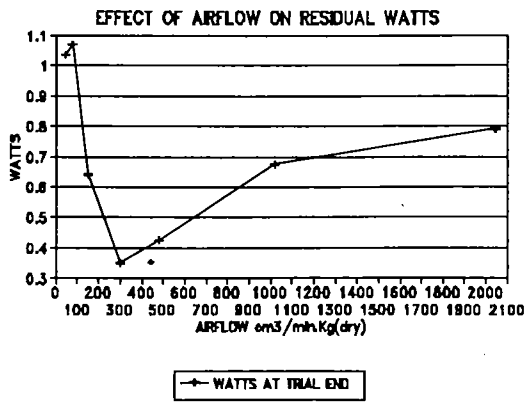


Figure 4.26

4.3.10 Composting outside of the reactors

A bag of compost was placed on the floor of the room in which the reactors were held.

Conditions surrounding the compost were not controlled, therefore heat production calculations could not be made.

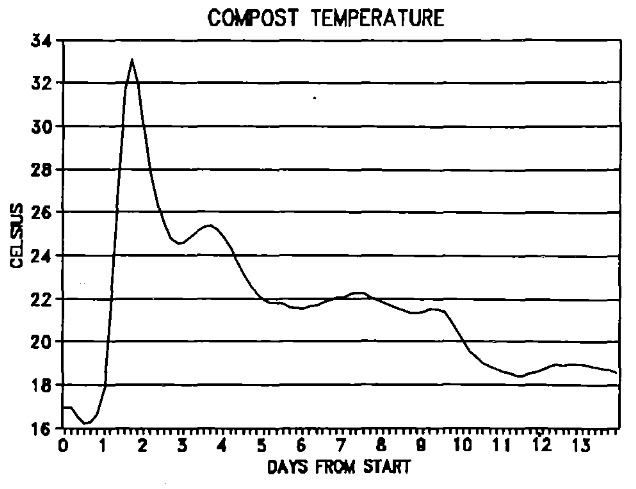


Figure 4.27 The temperature profile in a 16 litre reactor situated in a room at 14^{0}C.

Figure 4.27 shows the pile temperature 100mm from the surface. Calculation of organic matter oxidised by moisture balance was unreliable as the surface of the compost was very dry (26.8%), but when calculated from the moisture content of the middle of the reactor (60.2%), gave 6.1% organic matter oxidised. Ash analysis showed 10.9% organic matter oxidised. This is over half of the value from controlled airflow reactors (18%). The amount of composting that has occurred is consistent with the predictions of section 4.7; i.e. at an average compost temperature of 22^{0}C a composting time of 25 days would be expected (see figure 4.38 section 4.7). The trial only lasted 14 days therefore, over half the organic matter is oxidised in just over half the time.

This trial shows that composting is successful without controlled airflow, but temperatures are much lower and the time required to compost is longer than in a controlled airflow situation.

4.3.11 Effect of addition of urine

The upper limit of moisture content for successful composting is between 65% and 70%

moisture. Raw faeces are well over this limit at 80% moisture. Adding dry bulking material at the rate of 1.5:1 reduced the moisture content to 62%. This is close to the upper limit of the moisture content range. Addition of urine in large quantities to the compost would almost certainly increase moisture, but an equilibrium would be set up between urine added and drainage/evaporation losses. If the equilibrium moisture content is above the upper limit for aerobic composting, then it can be inferred that addition of urine will detrimentally affect the composting process.

To find the equilibrium moisture content for compost, a trial was done in which mature compost from the trials received a dose of water every hour. The compost was held in a mesh container 10cm diameter and 30cm high. 100 ml (50 ml in day 3) of tap water was added to the top of the compost every hour for a number of hours and then rested over-night, the process was repeated for three days. Moisture content samples were taken at the beginning and end of the trial. The compost and the amount of drainage were weighed before each addition of water.

Moisture content was assessed at each weighing by calculation from the dry weight at the start plus water retained. Figure 4.28 shows the results.

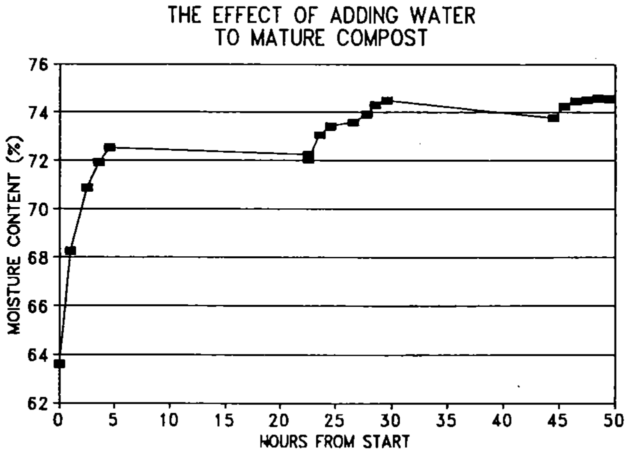


Figure 4.28

Moisture content continued to rise for three days and the equilibrium moisture content is 74.5%. The small loss of moisture overnight is due to evaporation, rather than drainage. The equilibrium moisture content is similar in magnitude to the sample from the Soltran (75.6%) and can be compared to Enferadis' (1981) data (up to 80%). Moisture content is above the level expected for good aerobic composting, suggesting that addition of urine to the compost is detrimentally affecting composting within a high use compost toilet.

4.4 COMPARISON OF HUMAN WITH PIG FAECES

Pig faeces were used because it was difficult to gain access to adequate quantities of human faeces (see also Jenkins, 1990). Pigs are mono-gastric and fed a diet similar to that of humans. Chemically the composition, of the faeces, is similar but the texture is different; clearly a trial had to be done to compare the composting performance of the two.

With the constraints on contributions, the reactors were only half full. Normally 6.7 kg of pig faeces were used in the 21 litre reactors. Only 2.8 kg of human faeces were available so the same weight of pig faeces were used. Bulking material ratio was left at 1.5:1. Toilet paper was inseparable from the human faeces so a similar quantity was added to the pig faeces. The reduced quantity of faeces produced a different temperature profile from previous trials.

The third reactor contained some of the poorly decomposed Soltran compost, mixed with sawdust (1.5:1). This was to see how much decomposition had occurred within the compost toilet. The Soltran compost was just over a year old.

Figure 4.29 shows the human faeces produced a much higher first peak. While the pig faeces produced a higher second peak.

Whether the differences are inherent between the two sources could not be established.

Differences could have arisen because the human samples were frozen shortly after emergence, whereas the pig faeces were collected from the floor of the pen. Some of the pig faeces would be several days old, and aerobic breakdown would have begun in this time, reducing the readily available energy sources for the first peak.

It was noted that initiation of composting in the pig reactor was un-characteristically delayed (normally initiation was less than 1 day; this trial it was 1.5 days). The pigs had not been: drenched for worms, diet changed, or any apparent factor that may influence the degradability of the faeces. Whether the delay in initiation was due to the small quantity in the reactor or other factors is unknown.

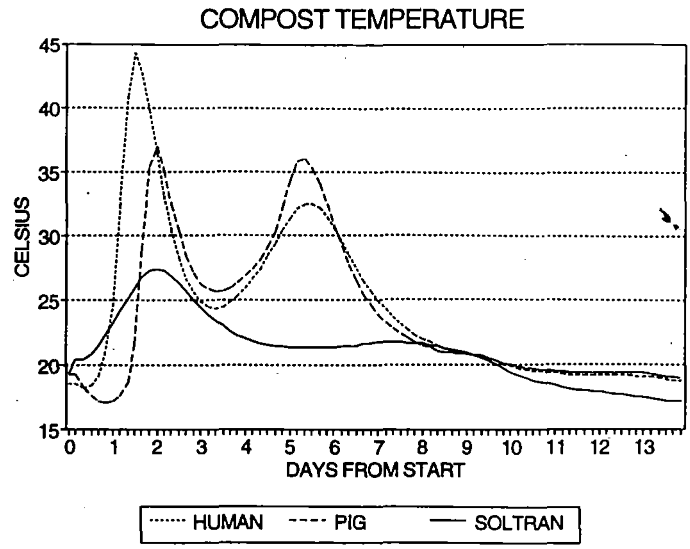


Figure 4.29

The temperature profile of the human and pig faeces are sufficiently similar to suggest the results of these trials are applicable to composting of human faeces. The differences between the two were mostly physical i.e. the human faeces were of a firmer consistency than the pig faeces and were more difficult to mix with the bulking material.

The Soltran compost warmed some 12^0C indicating that some of the original energy remained in the compost. The total Joules produced from the Soltran compost was 54% of that produced from the human faeces reactor (3334 versus 6145 kJ.). This indicated that even a poor performance in a compost toilet is going halfway to stabilising the faeces.

4.5 CORRELATION OF WATTS AND TEMPERATURE

Plotting watts against compost temperature produced a complicated, but interesting curve. Several features arose:

- a reasonably consistent mesophilic warming curve,
- a sharp drop at the mesophilic/thermophilic junction,

- a reasonably consistent thermophilic warming curve,

- a consistent cooling curve,

- occasional short term warming within this cooling curve,

- the rate of heat output at 40^0C (mesophilic) is similar to 50^0C-55^0C in the thermophilic,

- there were often, two peaks at the maximum thermophilic temperature.

A plot of trial 13 (mixing regimes) shows these features (figure 4.30).

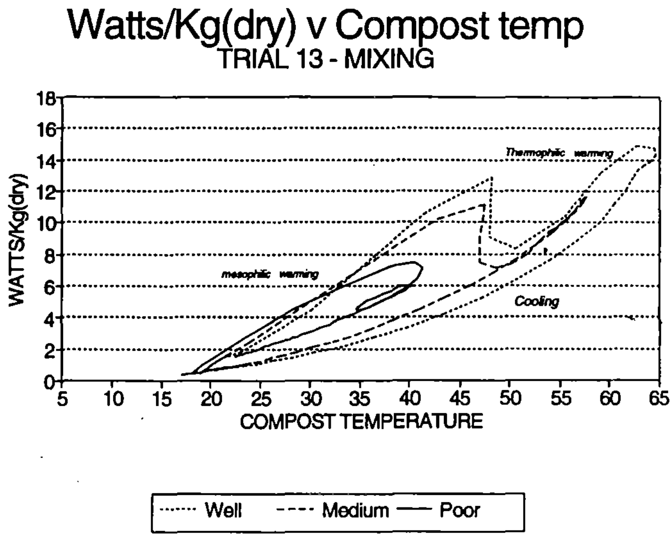


Figure 4.30

A linear regression was done on each section of the curve, using the data from three replicates with optimum conditions (i.e. 300 cm^3/min.kg airflow, well mixed, sawdust bulking material). This was repeated for the three optimum reactors from the cold room trials.

A/ Warm room (see figure 4.31)

Mesophilic warming $r^2 = .97$

$$Watts/kg(dry) = -.07797*t + .007781*t^2 - .5569$$

Thermophilic warming $r^2 = .91$

$$Watts/kg(dry) = -.43953*t + .008418*t^2 + 9.713$$

cooling phase $r^2 = .98$

$$Watts/kg(dry) = -.1841*t + .005871*t^2 + 1.94034$$

B/ Cool room (see figure 4.32)

Mesophilic warming $r^2 = .95$

$$\text{Watts/kg(dry)} = .151683*t + .001858*t^2 - .6413$$

Thermophilic warming

Did not reach thermophilic temperatures

Cooling phase $r^2 = .93$

$$\text{Watts/kg(dry)} = .046545*t + .003466*t^2 + .087$$

Plotted on a graph:

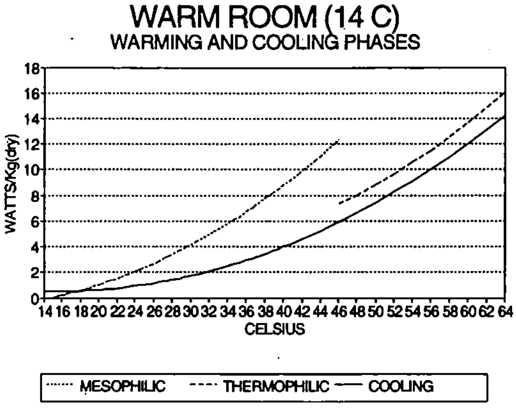


Figure 4.31

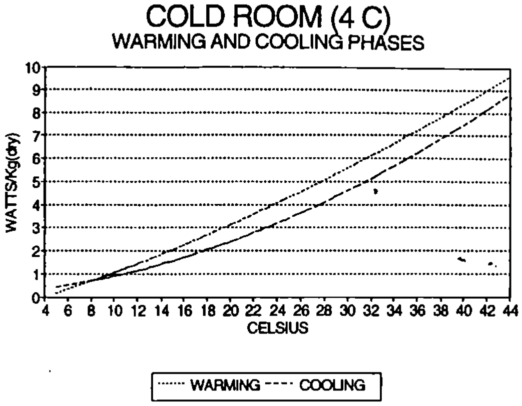


Figure 4.32

The slope of the warm and cold room profiles are different. The zero Watts intersection point in each case is very close to the room temperature setting (figure 4.33). This indicates that the microbial population adapts to the ambient temperature before composting starts. The literature supports microbial adaptation to ambient temperatures (McKinley *et al.*, 1985a) and Bartholomew and Norman (1953), found the time to initiation and the rate of warming differed with starting temperature.

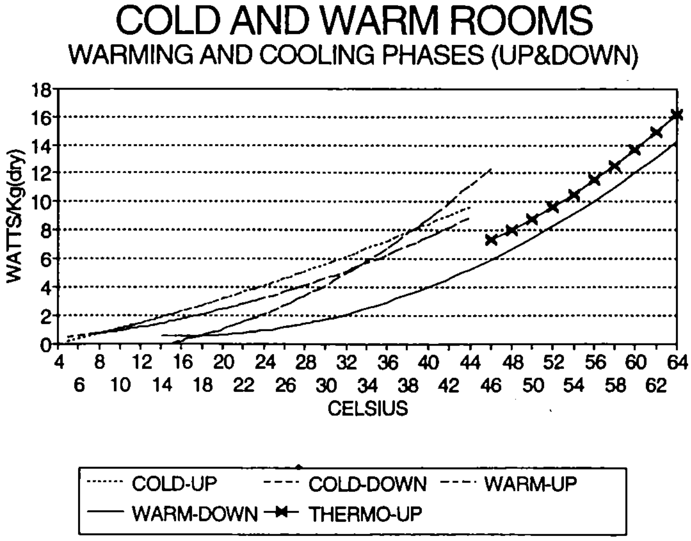


Figure 4.33 Graphs of the linear regressions of Cold room: (cold-up; cold-down) and warm room: (warm-up; warm-down; thermo-up)

The compost does not remain long at the highest temperature (4-8 hours) and cooling occurs relatively rapidly. The mechanism for this rapid cooling becomes apparent from the data.

4.6 COOLING MECHANISMS IN BATCH COMPOSTING

To understand cooling mechanisms in batch composting, consider the cold room profile (figure 4.32). The two curves are offset for most of the temperature range by about 1 watt (for any particular temp). At 40^0C the pile is producing 8.2 watts, thus a drop of 1 watt represents a 12% drop in heat output.

Most of the heat is lost by conduction with 3.7% lost by ventilation (see figure 4.3 -cold room). Thus, ventilation loss is related to conduction loss by:

$$Q_v = 0.037 Q_c \tag{4.1}$$

Where:	Q_v	= heat lost by ventilation	(W)
	Q_c	= heat lost by conduction	(W)

The formula for heat loss by conduction is:

$$Q_c = UA(t_m - t_a) \tag{4.2}$$

Where:	t_m	= air temperature around the compost pile
	t_a	= air temperature outside the reactors

Total heat losses can be got by adding ventilation and conduction:

$$Q_T = Q_c + Q_v \tag{4.3}$$

Where	Q_T	= total heat loss	(W)

substituting equation 4.1 in equation 4.3

$$Q_T = Q_c + .037 Q_c = Q_c * 1.037 \tag{4.4}$$

substituting equation 4.2 in equation 4.4

$$Q_T = UA(t_m - t_a) * 1.037 \tag{4.5}$$

Thus a 12% drop in heat output will give a 12% drop in temperature difference across the reactor wall.

A linear regression, using data from the three 'optimum' trials, showed that reactor air temperature (t_m) is related to the pile temperature (t_p) during the warming phase: $r^2 = .975$

$$t_m = .0967t_p + .00756t_p^2 + 3.77 \tag{4.6}$$

And during the cooling phase; $r^2 = .995$

$$t_m = .2559t_p + .00543t_p^2 + 2.65 \tag{4.7}$$

It has been established that heat production from the pile is also temperature dependent (section 4.5):

$$Q_{gain} = (xt_p + yt_p^2 + z) * 3.3 \tag{4.8}$$

Where:	Q_{gain}	= heat production	(W)
	3.3	= dry weight of compost in a reactor	(kg).

x,y,and z are constants that differ for the warming and the cooling curves.

At equilibrium, heat lost will equal heat gain. By plotting the heat lost from equation 4.5 and the heat gain from equation 4.8 against pile temperature, a visual assessment of the heat movements within the pile can be made (figure 4.34).

During the warming phase heat produced exceeds the heat lost with the difference going into storage and warming the pile (figure 4.34). The warmer pile is able to produce more heat etc. so the pile warms further.

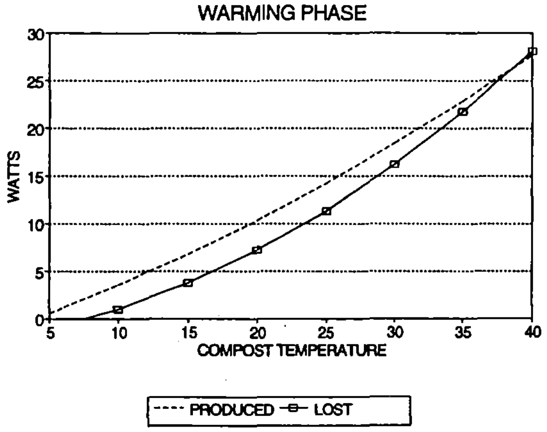


Figure 4.34 The heat produced Q_{gain} and heat lost Q_T plotted against compost temperature - Warming phase.

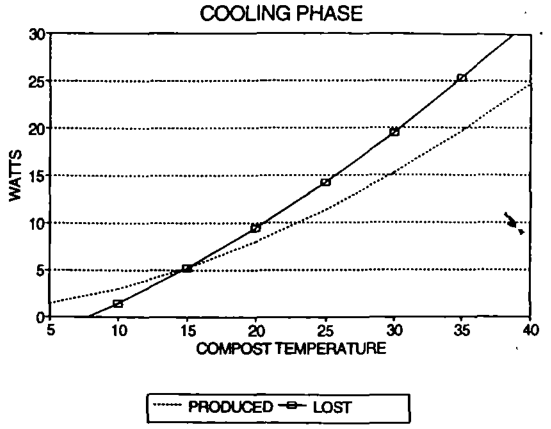


Figure 4.35 The heat produced Q_{gain} and heat lost Q_T plotted against compost temperature - Cooling phase.

The compost does not remain at maximum temperature, rather it rises to a maximum and begins to fall. It is within 1^0C of maximum temperature for 4-8 hours. The heat output begins to drop, and the relationship between compost pile temperature and reactor air temperature changes; thus the heat lost, changes with respect to pile temperature. This places the composting pile on the cooling curve where the heat lost exceeds the heat produced (figure 4.35). Heat is removed from storage and the temperature falls. As the temperature falls the amount of heat produced falls and so on. Equilibrium will only be reached at the point where heat production = heat loss. This point occurs at 15^0C.

In effect the pile is placed on an inevitable temperature fall scenario. The fall in temperature cannot be avoided, unless a new source of energy becomes available to the micro-organisms (this occurs in some instances and can be seen in figure 4.30 (poor), where some energy source still remains and presumably the pile reaches a temperature which is favourable to the organism or enzyme system able to utilise the source).

The dominant influence in the cooling of a compost pile is thus the pile temperature/heat output effect. The catalyst setting off the decline is a drop in heat output (exhaustion of an energy source within the pile), but the drop is **maintained** by the characteristics of the temperature/heat output curve.

The curves calculated above, will contain both temperature and substrate/microbe effects. The majority of the effect during the warming phase is likely to be temperature induced, as the microbial biomass would have had little chance to respond to the rapidly changing conditions (one day from cold to hot). The cooling curves, on the other hand, occurred over a much longer time period (5 days), so it is likely that substrate/microbe interactions (especially exhaustion of energy supplies) could have played a significant role.

To establish whether the cooling phase is dominated by temperature or substrate effects, a trial was run in which the room temperature was raised as the compost cooled off, the intention being to maintain the pile temperature close to 37^{0}C. If the dominant effect is temperature, then the heat output (Watts) should remain at the level expected for that temperature. If it falls off, then this will be an indication of the contribution of substrate depletion, to the temperature decline section of the curve.

In the trial, the pile temperature continued to cool as the room was warmed to 30^{0}C over an 8 hour period. The hourly data covering 2 days either side of the room warming, reveal some interesting effects (figure 4.36). The surface of the compost began to warm 5 hours after the room temperature was first altered. The rate of heat output and pile temperature continued to decline for a further 3 hours **after** the surface had begun to warm (8 hours after the room temperature was first changed). The rate of heat output changed when the centre of the pile began to warm.

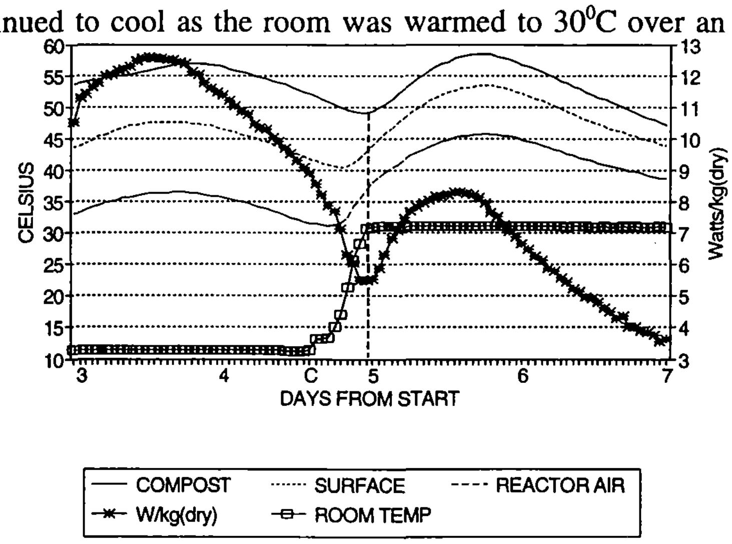


Figure 4.36 The effect of changing room temperature as compost pile cools; where c = time when room temperature was first changed.

The concurrence of the minimum heat output and minimum pile temperature, indicate that the surface of the pile is exhausted of compostable nutrients, but that nutrients still remain in the core of the compost. This strongly suggests that the mechanism for the decline in pile temperature from the thermophilic peak is due to exhaustion of the *surface layer* of the pile.

This conclusion also indicates why the heat versus temperature curve for cooling of the compost is displaced from the warming curve. If the outer layers become progressively exhausted, then the mass of compost actively contributing heat will decrease. The rate of heat output as calculated (Watts/kg(dry)), assumes a constant amount of compost contributing the heat. The Watts versus temperature curve, as plotted, will thus be displaced downwards as the surface layers become exhausted.

This effect is noted in all three reactors where the temperature peak after warming of the room (day 6 in figure 4.36), occurs below the cooling curve that was expressing itself before the room temperature was raised (figure 4.37).

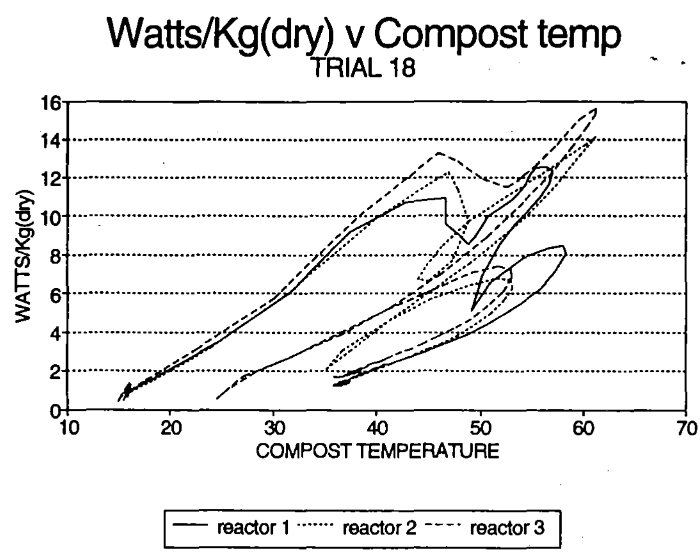


Figure 4.37

This analysis indicates the extreme sensitivity of the temperature of a compost pile to the rate of heat output of the material being composted. It points to the difficulty that compost toilets have in maintaining hot piles.

4.7 ESTIMATING THE TIME REQUIRED FOR COMPOSTING TO BE COMPLETED

The preceding results and discussion apply to a batch loaded composting system whereas most compost toilets operate on a continuous basis i.e. they receive additions each day. To derive formulas from these results that can be applied to compost toilets in general, requires some assumptions to be made:

1/ compost toilet pile temperatures fluctuate within narrow limits (see figure 3.5).

2/ that the temperature effect on heat output noted in section 4.5 can be applied to a continuous system.

3/ under conditions of constant temperature, an individual particle is considered to produce energy at a steady rate until exhausted.

Assumption 3 is made to simplify calculations. It has been shown to be not true (Pressel and Bidlingmaier, 1981). Each individual particle has a "life cycle", in that it exhibits a heat output (oxygen consumption) profile similar to that of a batch loaded profile i.e. a delay in initiation of composting, heat output rising to a high as the readily available energy sources are used, followed by a decline in energy output as the more refractory organics are composted. It is felt that the error introduced by this assumption will not materially affect the usefulness of the equations. Composting will continue at a low rate for a longer period of time, but the faeces will be almost fully composted and not offensive. Trials to test the second assumption were not carried out as part of this thesis but there is evidence to support its validity. First, section 4.6 established that the reason for the cooling curve to be off-set from the warming curve is exhaustion of the surface layers of compost and that if only the compost that was contributing heat was used to calculate heat output, then the cooling curve would have been much closer to the warming curve. In other words, all the time series data from the trials would follow, reasonably closely, the warming section of the heat output versus temperature curve. Second, the reaction rate constant discussed in section 2.2, supports the general form of the heat output versus temperature curve. Thus, while an accurate correlation will only be possible with experimentation, the application of the principle will remain.

Using assumptions 2 and 3, an estimate of the time required for composting to be completed can be made by combining the rate of heat output for the average pile temperature (section 4.5), with the known amount of energy available in faeces.

Total energy = rate of heat production * time

$$Total\ energy = Q * days * 86400 \tag{4.9}$$

$$Q = f(t) = xt_p + yt_p^2 + z \tag{4.10}$$

Rearranging equation 4.9 and substituting equation 4.10:

$$days = \frac{Total\ energy}{Q*86400} = \frac{Total\ energy}{(xt_p + yt_p^2 + z)86400} \tag{4.11}$$

The total energy available in human faeces is 21.5 MJ/kg(dry) (Lentner, 1981) and it is also known that 36% of organic matter is oxidised during composting. Therefore 7.7 MJ/kg(dry) is available.

Placing these values in equation 4.11 and using x,y,and z from the mesophilic warming phase of the cold room (section 4.5) gives:

$$days = \frac{7.7*10^6}{(0.1517t_p + 0.00186t_p^2 - .641)86400} \tag{4.12}$$

This was repeated for the warm room values of x,y, and z and plotted on a graph (figure 4.38):

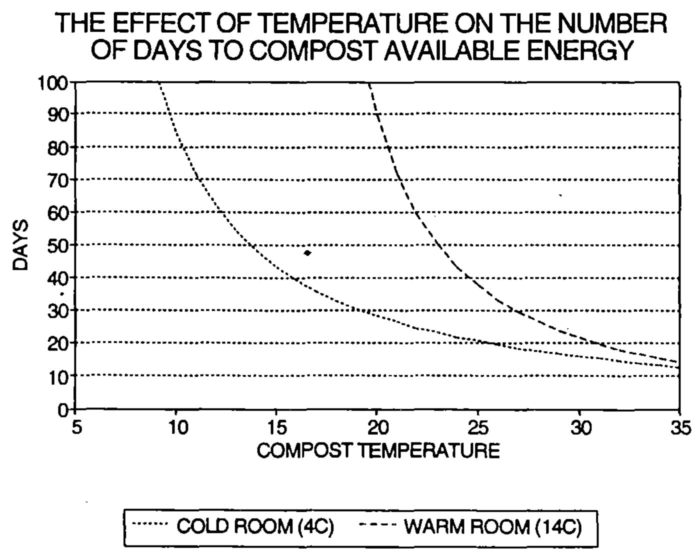


Figure 4.38

It should be noted, that the curves were derived from temperature at the centre of the pile in a batch composting system using non-degradable bulking material. A continuous system (compost toilet) would not have such rapidly changing conditions, and there would be greater stability in the microbial population. Therefore *note, that these results may **not** be directly applicable to continuous use compost toilets.* In particular the results close to the trial room temperature, (4^0C and 14^0C) are suspect. This is because at the start of each run, heat output rose quickly from zero; what proportion of this rise was heat induced and what was due to microbial changes as composting initiated is not known. In other words, the first few hours of a batch system may better represent microbial adaptation to the new environmental conditions following mixing, rather than a response to temperature. The relationship between heat output and temperature for continuous systems could not be established from this research as a reactor design, that allows fresh material to be added and exhausted compost removed without opening the reactor (and affecting the validity of the energy balance with an unknown ventilation component), is not available.

The curves approach each other above 30^0C which suggests that either curve could be used at higher temperatures. Generally, the cold temperature curve would be the most reliable, as the chaos of the first few hours of a radically altered environment are well removed from any actual temperature rise (it was several days before composting was initiated). Thus *the cold temperature profile will better represent conditions in a compost toilet.*

4.8 ESTIMATING TOILET OVERLOAD POINTS

Knowing the days required to compost, it is then possible to show whether the toilet is overloaded. The depth of burial in the time taken to compost, will be:

$$\textit{Depth of burial} = \frac{[(N*S)+BM]*days}{A} \tag{4.13}$$

N	= number of users/carousel.day	(person)
S	= 135 (faeces contribution)	(cm^3/day.person)
BM	= bulking material added	(cm^3/day)
A	= horizontal surface area of the compost	(cm^2)
days	= time to compost	(days)

Note: the quantity/user (S) will depend on type of use i.e. whether day use, or overnight use. Day use will produce more urine and less faeces than overnight use. Gotaas (1956) noted a range of 135-270 gms wet weight faeces, and Lentner (1981) measured density at 1.09. The lower limit of production is used, as N is based on bed-nights at the hut and not everyone will defecate.

For the Soltran at a use level of 25 people/day, divided between two units:

N	=12	people
P	=135	cm^3/day.person
A	=2827	cm^2
BM	=2000	cm^3/day

COMPOST TEMPERATURE °C	DAYS REQUIRED TO COMPLETE COMPOSTING	DEPTH OF BURIAL BEFORE COMPOSTING IS COMPLETE (cm)	COMMENTS
16	39	50	Early season temp.
20	28	36	
25	21	26	Average mid-season temp.
30	16	20	
35	13	16	Maximum recorded

Table 4.6 The effect of compost pile temperature on depth of burial before composting is complete - Based on the Soltran toilet with a use rate of 12 people/day.

The depth of oxygen penetration in a high use compost toilet is not known, but will depend on porosity, moisture content and the rate of composting in the surface layer. These trials have shown that the core of a high rate batch composting pile composts successfully, albeit slightly delayed with respect to the surface, at a depth of 15 cm (reactor is 30 cm diameter). The depth of oxygen penetration in a low temperature compost pile would be greater than in a high rate compost, as the 'scavenging effect' on oxygen (consumption by the compost) would be less at low composting rates, allowing deeper diffusion of the oxygen. Oxygen penetration in a toilet, therefore, would be greater than 15cm.

An estimate of the depth at which oxygen penetrated into the Soltran can be made. Trial 15 showed that the poorly decomposed Soltran compost has lost only half of its available energy (section 4.4). The compost temperature in the early season compost is typically 16^{0}C with a burial depth of 50 cm. This suggests oxygen penetration is around 25 cm with the pile conditions found in an operating compost toilet (urine drains through the pile).

It would seem, from table 4.6, that depth of burial is limiting the compost process during the colder, early part of the season, but this limitation is removed as the compost warms throughout the season. This is consistent with observations made during emptying of the toilet (Chapman, 1989), where the poorly decomposed compost was generally located in the lower part of the chamber; and most commonly in those chambers started early in the season. It is also consistent with the observations of Smith (1981), although he had no record of the usage history of the toilets.

Despite uncertainty in the applicability of the Watts curve to continuous systems, and the effect of urine addition to compost, it is useful to calculate the hut loading rates as influenced by compost temperature. Use of temperature at the centre of the pile is satisfactory for this, as a compost toilet would show similar temperature gradients from the centre to the edge. Hut loading rates are calculated by rearranging equation 4.13 and assuming that bulking material addition will vary according to hut usage rate i.e. BM=N*167 (bulking material ratio of 1.23:1). If the depth of burial before composting is complete equals the depth of oxygen penetration, then the upper usage rate for full aerobic composting can be calculated:

$$N = \frac{Oxygen\ penetration\ depth * A}{days * (135 + BM_p)} \tag{4.14}$$

where: BM_p =bulking material added per person cm^3/person

Figure 4.39 shows how loading rates vary with pile temperatures. Two burial depths, 25cm and 35cm, give a grey area between overload and safe loadings, acknowledging the uncertainty in the derivation of the Watts/temperature curve, the effect of urine and the entirely speculative nature of the actual depth that oxygen becomes limiting.

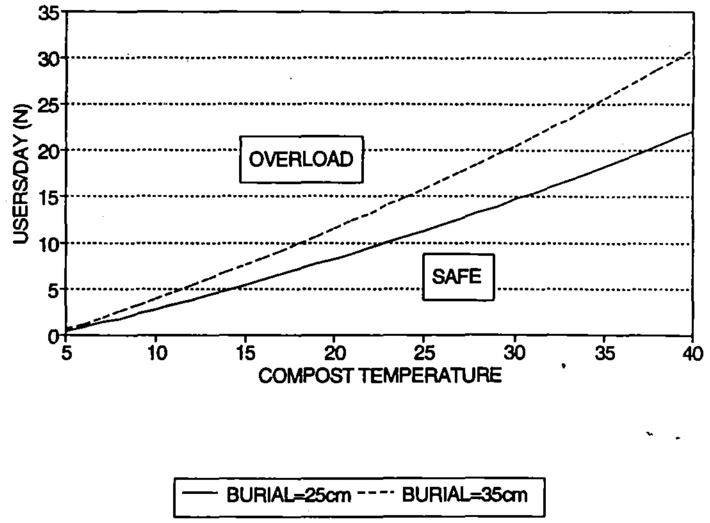


Figure 4.39 The effect of compost temperature on number of users before overload conditions occur. Based on the Soltran toilet.

4.8.1 Optimising the carousel rotation

Knowing the number of days required to compost enables the carousel change-over times to be optimised. To achieve this, consider the early season temperature which requires 39 days to compost the available energy (table 4.6).

There are four quadrants in the carousel, one will be filling while the other three are composting. If each quadrant were filled for the same period of time (D), then the rest period will be 3D. If the rest period needs to be 39 days, then the rotation length (D) will need to be 39/3 = 13 days. However composting will also be occurring as the quadrant fills so the days to compost could be divided by 4 i.e. 39/4 = 10 days. The rotation length currently used is 3 weeks (21 days), so some improvement in compost quality can be expected if the rotation length were reduced to 2 weeks/quadrant at the first rotation. The rotation could be as short as 1 week/quadrant when the compost has warmed to 30^{0}C. Note: this analysis is based on a hut usage of 24 people/day (12 people/toilet).

4.8.2 The effect of poor mixing on the time required to compost.

Figure 4.30 shows that well mixed compost has a concave Watts/temperature curve, while the poor mixed shows a convex curve. Most differences, however, occur at higher temperatures. At the operating temperature of a compost toilet (25^{0}C), the curves are similar, suggesting only a small temperature effect on the number of days required to compost available energy, and consequently the depth of burial before composting is complete.

The reason why the poorly mixed reactor did not reach thermophilic temperatures, is the flattening of the curve at higher temperatures. This will cause the heat produced to equate heat lost at a lower temperature (consider figure 4.34 with a convex, rather than concave, heat production curve; it will quickly meet the concave heat lost curve).

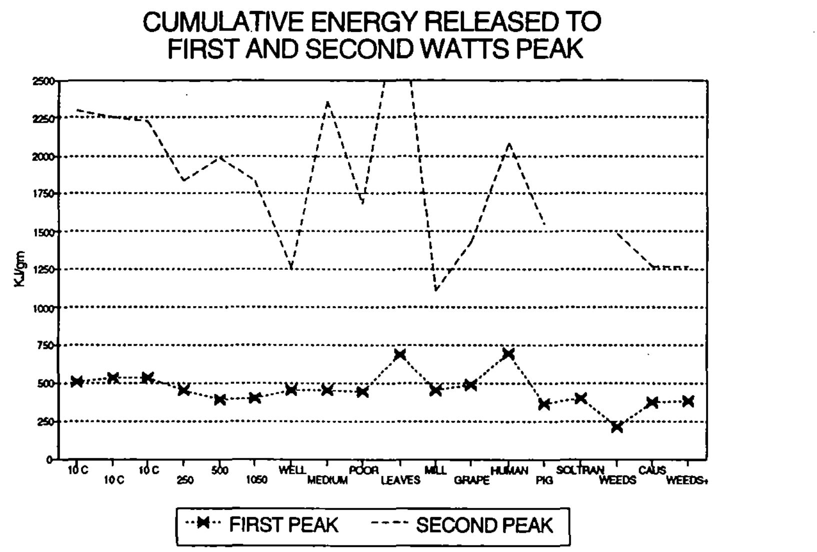


Figure 4.40

The reason why the curve is shaped this way is not clear. There is a delay in initiation (0.33 day as against 0.17 day), and it is known that the cumulative Joules to the first Watts peak are similar (figure 4.40). Neither of these explain why the heat output can be similar at low temperatures, but differ at higher temperatures.

It is possible that mixing impacts on the depth that oxygen will penetrates, rather than the rate of composting itself. This could not be assessed from these trials.

4.9 DISCUSSION

This research aimed to assess how applicable the research, that has been done for large scale composting, is to compost toilets (small scale). The differences between large scale and small scale composting piles are identified as: the high proportion of heat loss due to conduction, the importance of evaporative cooling in an uncontrolled airflow situation, the importance of composting at the surface (edge effects), the nature of the Watts/temperature effect, and the effect of addition of urine.

This research confirms that temperature of the pile influences the speed of composting more than any other factor. Achieving thermophilic temperatures in a compost toilet (and consequently a high rate of composting), by retention of biological heat produced, will be difficult. This is because:

1/ airflow needs to be controlled to minimise evaporative cooling (this is counter to the requirement for odour removal),

2/ the nature of the Watts/temperature relationship implies that, for any combination of insulation/surface area of reactor, there is a minimum energy density required before the pile will rise to thermophilic temperatures. This minimum density will be difficult to achieve with continuous addition of waste, without having continuous removal of exhausted compost.

This suggests that a high rate thermophilic compost toilet will be difficult to achieve. However a design that operates at optimum mesophilic temperatures (30^0C-40^0C) is possible. Such a toilet would: handle high loading rates, be able to operate in cold environments, and would be more likely to produce a pathogen free compost than designs that operate close to ambient temperatures.

This research has also shown that composting will initiate at 4^0C, and there is no threshold temperature (above 4^0C) for successful composting. Temperature limits the composting process, in a toilet pile, by slowing the rate of composting to the point where the depth that the compost is buried before composting is completed, is beyond the limits of oxygen penetration. Thus the usage level at which the toilet will be overloaded is, in part, temperature dependent, in part dependent in the surface area of the compost, and in part dependent on oxygen penetration depth. A formula is proposed to calculate this level of usage.

The other factor that influences the overload of a compost toilet is urine. Addition of urine causes the pile moisture content to rise to levels that will adversely affect composting by restricting oxygen penetration into the pile. Separation of urine is essential in a high use compost toilet. Evaporation may lower moisture content to acceptable levels in a low use toilet (long time period between liquid additions), and one with auxiliary heating (additional energy). However, evaporation of excess moisture from the pile is contrary to the requirements for retention of heat in the pile (heat retention impacts on speed of composting). Therefore separation of urine at source is better than evaporation from the pile. Thus urine impacts on two aspects of equation 4.14 i.e. oxygen penetration depth and the number of days required to compost.

Degradable bulking material will release more energy, and cause the pile to be warmer than if a non degradable bulking material (sawdust) was used. However, using a degradable bulking material also results in compaction of the pile (structural collapse) and this could adversely impact on penetration of oxygen into the pile. The overall benefit of a degradable bulking material is not clear from this research.

Having bulking material well mixed in, impacts on high rate composting, but appears to have less impact on the rate of composting at toilet operating temperatures. Mixing is more likely to adversely impact on oxygen penetration depth, than the rate of composting. The lack of an effect of mixing on the rate of composting at toilet temperatures, is inferred from the results so cannot be confirmed from this research.

One of the management dilemmas for a public facility compost toilet is the requirement for bulking material. This is done at the Soltran by wardens based at the hut, but elsewhere it could be seen as an additional operating cost, above normal cleaning requirements. It would be desirable to automate the addition of bulking material, so users can "flush" the toilet after use. The "flush" would add bulking material. With such a device, management responsibility would be to keep the bulking material container full (this could be done as part of routine cleaning operations).

4.10 <u>FURTHER RESEARCH NEEDED</u>

This research has been conducted using batch loaded reactors. It would be desirable to devise a continuous addition reactor that allowed heat production to be calculated. With such a reactor a better understanding of compost toilet processes could be obtained. Aspects that could not be answered by the type of reactor used in these trials are:

- how does initial mixing impact on composting rate in a continuous composting system?
- the Watts/temperature curve needs to be established for continuous systems.
- what is the effect of air conditions, especially humidity, on composting in the surface layer?

The effect of urine addition on the composting process needs more research: how does mixing and bulking material particle size affect the equilibrium moisture content (just as sandy soils get less waterlogged than clay soils)? What is the moisture content before human faecal waste composting is significantly affected, and is this level affected by the amount of mixing and type of bulking material? Do urine effects have more impact in high use, rather than low use toilets? What are the impacts on pile temperatures, of evaporating urine from the pile?

In addition, it would be desirable to know the depth of oxygen penetration into a pile and how this is affected by initial mixing, size of bulking material, the rate of composting in the surface layer, and addition of urine?

The effectiveness of mesophilic composting (35^0C-40^0C), at destruction of pathogens needs to be established.

With this additional research, it would be possible to accurately quantify the conditions (pile temperature and usage level) at which compost toilets would be likely to fail. Alternatively equation 4.14 could be modified to enable a choice to be made (based on usage rate and site), as to the degree of sophistication required in a compost toilet and/or number of toilets that would perform satisfactorily at a particular site.

CHAPTER 5

5.1 CONCLUSION

Compost toilets are a desirable method for human faecal waste disposal from the perspective of off-site pollution. They have the potential to be an ideal toilet for remote sites, however some units have failed in operation and the failure rate appears to be higher with public facilities. The mechanisms causing this failure have not been documented in the literature.

This research has identified two areas which contribute to failure of composting, although it has not been possible to establish which one dominates. Addition of urine raises the moisture content of the pile to levels beyond those associated with successful composting, while low pile temperatures (in part caused by excess liquid) delay completion of composting, with the result that raw faeces are buried beyond the limits of penetration of oxygen.

Three aspects of a compost toilet operation conflict with the requirements for retention of heat within the pile:

- liquid evaporation causes evaporative cooling,
- odour removal needs a high airflow resulting in heat loss,
- 1 or more years storage require a container with a large surface area (increased heat loss).

This research finds that composting systems occur on a continuum between the ambient air, 'forest floor ecosystem' composting of existing, double vault toilet designs; and high temperature, 'bacterially dominated' high rate composting found in well aerated large piles. Airflow (and its associated evaporative cooling) is the link that determines the position on the continuum.

At the controlled airflow extreme of this continuum is a toilet that retains much of the biological heat produced and warms up. The heat produced by composting faeces is low (2.4 Watts/user) and is independent of operating temperature in a continuous use toilet. To retain this heat and achieve a warm pile, will require efficient insulation, a small container and minimum evaporation. The toilet will respond to increased use by increasing pile temperature.

At the other extreme of the continuum is a large, un-insulated container with high airflow removing odours i.e. a large hole in the ground, in effect a double vault compost toilet, as used in several parts of the world.

This research has found that, above 4^0C there is no minimum threshold temperature for successful composting (success in this context is confined to stabilisation/smell considerations, it does not include pathogen destruction i.e. the compost is OK to dig out without a peg on the nose). Therefore successful composting is possible in any situation where urine can be separated from the faeces, bulking material can be added, and the surface area over which the fresh compost is spread is large enough to allow composting to be completed before it is buried too deep. The time for complete composting is temperature dependent and the depth of burial is dependent on the number of people using the toilet.

With these requirements for composting, the need for a sophisticated container to store the compost can be questioned. The requirements can be met by almost any container or hole in the ground (see appendix 3 for the elements required in an ambient temperature compost toilet). Such a toilet system would cost little, yet improve the user acceptability of many of the DoC's toilet requirements

Existing toilet designs cannot retain biological heat because of their high airflow requirement, but because of restricted surface area (partly caused by costs of manufacture) do not exist at the lower end of the continuum. They are neither one nor the other.

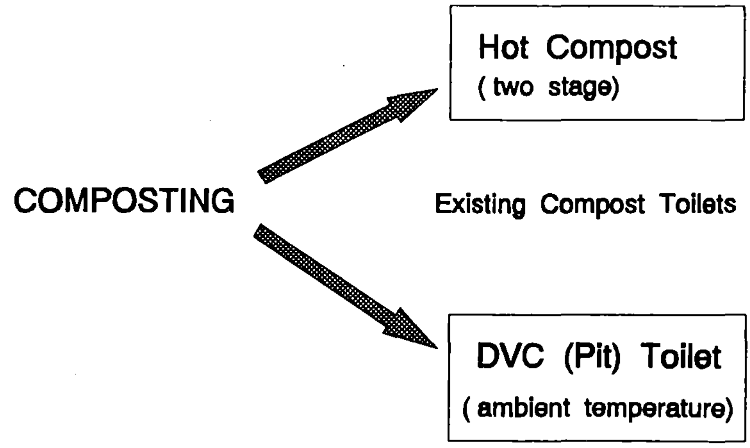


Figure 5.1 Where compost toilets fit in the composting continuum.

Analysis of the Soltran data has shown that it is difficult to combine the requirements of evaporation, with heat transfer. However there is a possibility of combining evaporation/condensation as a heat transfer mechanism with collection and disposal of the condensed (purified?) water.

Complete evaporation of all liquids at a cold, low sunshine hour site would be possible, but a better option would be separate collection and disposal of the relatively non-contaminated urine. This would improve composting performance, with little risk of contamination from disposal of the urine, as many of the potential water-borne diseases, such as giardia, are not present in urine.

BIBLIOGRAPHY

AMPOFO,E.; FOX,E.G.; SHAW,C.P.. (1991). *Giardia and giardiasis in New Zealand - A review.* Department of Health, Wellington.

ASHBOLT,N.J.; LINE,M.A.. (1982). A bench-scale system to study the composting of organic wastes. *Journal of Environmental Quality* 11(3):405-408.

ASHRAE. (1989). *ASHRAE handbook - Fundamentals.* American Society of Heating, Refrigerating, and Air Conditioning Engineers.

BAGSTAM,G.; ENEBO,L.; LINDELL,T.; SWENSSON,H.. (1974). Experiments made in bench scale composters. 1. Apparatus. *Vatten* 4.74:358-363.

BAGSTAM,G.; SWENSSON,H.. (1976). Experiments made in bench scale composters. 2. Composting of spruce-bark. *Vatten* 1.76:45-53.

BARTHOLOMEW,W.V.; NORMAN,A.G.. (1953). Microbial thermogenesis in the decomposition of plant materials; IV. Influence of moisture content and of initial temperature. *Journal of Bacteriology* 65:228-233.

BERNHART,A.P.. (1973). *Treatment and disposal of waste water from homes by soil filtration and evapo-transpiration.* University of Toronto Press.

BLOBAUM,R.. (1975). China recycles her wastes by using them on the land. *Compost Science* 16(5):16-17.

BROOKER,D.B.; BAKKER-ARKEMA,F.W.; HALL,C.W.. (1974). *Drying of cereal grains.* The AVI Publishing Company.

BURGE,W.D.; ENKIRI,N.K.; HUSSONG,D.. (1987). Salmonella regrowth in compost as influenced by substrate (Salmonella Regrowth in Compost). *Microbial Ecology* 14:243-253.

CAMPBELL,C.D.; DARBYSHIRE,J.F.; ANDERSON,J.G.. (1990a). The composting of tree bark in small reactors - self-heating experiments. *Biological Wastes* 31:145-161.

CAMPBELL,C.D.; DARBYSHIRE,J.F.; ANDERSON,J.G.. (1990b). The composting of tree bark in small reactors - adiabatic and fixed-temperature experiments. *Biological Wastes* 31:175-185.

CARMICHAEL,R.C.; COLLINS,M.A.; ASCE,M.. (1989). Experimental study of windrow composting of sludge . *Environmental Engineering. Proceedings of The 1989 Speciality Conference.* Edited by J.F. Malinga.: American Society of Civil Engineers, New York.

CHAPMAN,P.D.. (1989). *Soltran composting reports 1989-91.* Department of Conservation - internal report.

COOPER,R.C.; GOLUEKE,C.G.. (1979). Survival of enteric bacteria and viruses in compost and its leachate. *Compost Science/Land Utilisation* 20(2):29-35.

CRENNAN,L.. (1992a). *Composting toilet project- Report No 4: Rota-loo composting toilets in Tasmanian National Parks.* Centre for Environmental Studies, University of Tasmania.

CRENNAN,L.. (1992b). *Composting toilet project- Report No 5: Clivus Multrums on the east coast of Australia.* Centre for Environmental Studies, University of Tasmania.

CRENNAN,L.. (1992c). *Waste in troubled waters: A case for alternative sewage treatment.* University of Tasmania: Environmental studies working paper #22.

DE BERTOLDI,M.; CITERNESI,U.; GRISELLI,M.. (1980). Bulking agents in sludge composting. *Compost Science/Land Utilisation* 21(1):32-35.

DE BERTOLDI,M.; VALLINI,G.; PERA,A.. (1985). Technological aspects of composting including modelling and microbiology. *Composting of Agricultural and Other Wastes: Proceedings of a seminar organised by the Commission of the European*

Communities, Directorate-General Science, Research and Development, Environment Research Programme, held at Brasenose College, Oxford, UK, 19-20 March 1984. Edited by Gasser J.K.B.: Elsevier Applied Science.

DE BERTOLDI,M.; ZUCCONI,F.; CIVILINI,M.. (1988). Temperature, pathogen control and product quality. *Biocycle* 29(2):43-50.

DEPARTMENT OF CONSERVATION. (1991). *Giardia report - Part A - Report of the Giardia testing programme.* Resource use and Recreation Division. Department of Conservation, Wellington.

DESCHAMPS,A.M.; HENNO,P.; PERNELLE,C.; CAIGNAULT,L.; LEBEAULT,J.M.. (1979). Bench-scale reactors for composting research. *Biotechnology Letters* 1:239-244.

EDWARDS,C.. (1990). *Microbiology of extreme environments.* McGraw-Hill Publishing.

ELY,J.F.; SPENCER,E.L.. (1978). *The composting alternative: waste disposal in remote locations.* Appalachian Mountain Club: A report to the N.H. Water Supply and Pollution Control Commission.

ENFERADI,K.M.. (1981). A field evaluation of the waterless toilet as an alternative to the failing soil absorption system. In: *Individual onsite wastewater systems - Proceedings of the NSF eighth national conference 1981*: 201-209.

ENGELDER,C.L.; ALLEMAN,J.E.; SCHOLZE,R.J.; SMITH,E.D.. (1986). Innovative airflow design for compost toilets. *Biocycle* 27:40-41.

EPS. (1985). Sewage lagoons in cold climates. *Canadian Environmental Protection Service. Report*: EPS 4/nr/1.

FEACHEM,R.G.; BRADLEY,D.J.; GARELICK,H.; MARA,D.D.. (1983). *Sanitation and disease: health aspects of excreta and wastewater management.* John Wiley and Sons: World Bank:Vol.3 of series.

FERNANDES,F.; VIEL,M.; SAYAG,D.; ANDRE,L.. (1988). Microbial breakdown of fats through in-vessel co-composting of agricultural and urban wastes. *Biological Wastes* 26:33-48.

FINSTEIN,M.S.; MORRIS,M.L.. (1975). Microbiology of municipal solid waste composting. *Advances in Applied Microbiology* 19:113-151.

FINSTEIN,M.S.; MILLER,F.C.; STROM,P.F.. (1986). Monitoring and evaluating composting process performance. *Journal of the Water Pollution Control Federation* 58(4):272-278.

FLOOD,C.A.; KOON,J.L.; TRUMBULL,R.D.; BREWER,R.N.. (1987). Equilibrium moisture relations for pine shavings poultry litter material. *Transactions of the American Society of Agricultural Engineers* 30(3):848-852.

FRANKOS,N.H.; GOUIN,F.; SIKORA,L.J.. (1982). Using woodchips of specific species in composting. *Biocycle* 23(3):38-40.

GABY,N.S.; CREEK,L.L.; GABY,W.L.. (1972). A study of the bacterial ecology of composting and the use of *Proteus* as an indicator organism of solid waste. *Developments in Industrial Microbiology* 13:24-29.

GOLUEKE,C.G.. (1981). Principles of biological resource recovery. *Biocycle* 22(4):36-40.

GOLUEKE,C.G.. (1982). When is compost "safe"?. *Biocycle* 23(2):28-36.

GOLUEKE,C.G.. (1986). Compost research accomplishments and needs. *Biocycle* 27(4):40-43.

GOLUEKE,C.G.. (1992). Bacteriology of composting. *Biocycle* 33(1):55-57.

GOTAAS,H.B.. (1956). *Composting: sanitary disposal and reclamation of organic wastes.* World Health Organisation, Geneva.

GUNN,I.. (1991). *Composting and dry vault household toilet systems - current status, December 1991.* Auckland University.

HANDRECK,K.A.. (1990). *Composting: making soil improver from rubbish.* CSIRO Melbourne.

HAUG,R.T.. (1979). Engineering principles of sludge composting. *Journal of the Water Pollution Control Federation* 51(8):2189-2206.

HAUG,R.T.. (1980). *Compost engineering principles and practice.* Ann Arbor Science, Michigan.

HAUG,R.T.. (1986a). Composting process design criteria - Part 1 Feed conditioning. *Biocycle* 27(7):38-43.

HAUG,R.T.. (1986b). Composting process design criteria - Part 111 - Aeration. *Biocycle* 27(9):53-57.

HAUG,R.T.; ELLSWORTH,W.F.. (1991). Measuring compost substrate degradability. *Biocycle* 32(1):56-62.

HAY,J.; AHN,H.; CHANG,S.; CABALLERO,R.; KELLOG,H.. (1988a). Alternative bulking agent for sludge composting - Part 1. *Biocycle* 29(9):48-52.

HAY,J.; AHN,H.; CHANG,S.; CABALLERO,R.; KELLOG,H.. (1988b). Alternative bulking agent for sludge composting - Part II. *Biocycle* 29(10):46-51.

HUGHES,E.G.. (1980). The composting of municipal wastes. In: *Handbook of Organic Waste Conversion.* Edited by Bewick,M.W.M.: Van Nostrand Reinhold Environmental Engineering Series.

INBAR,Y.; CHEN,Y.; HADAR,Y.; VERDONCK,O.. (1988). Composting of agricultural wastes for their use as container media: simulation of the composting process. *Biological Wastes* 26:247-259.

INCROPERA,F.P.; DEWITT,D.P.. (1985). *Fundamentals of heat and mass transfer.* John Wiley and Sons.

JAMES,T.I.. (1991). *Biochemical characterisation and microbial degradation of a pulp mill waste liquor.* Thesis for Master of Science (Biotechnology); University of Canterbury.

JENKINS,T.. (1990). Thesis. *Canterbury University.*

JERIS,J.S.; REGAN,R.W.. (1973a). Controlling environmental parameters for optimum composting: part 1 experimental procedures and temperature. *Compost Science* 14(1):10-15.

JERIS,J.S.; REGAN,R.W.. (1973b). Controlling environmental parameters for optimum composting: part 2 Moisture, free air space, and recycle. *Compost Science* 14(2):8-15.

JERIS,J.S.; REGAN,R.W.. (1973c). Controlling environmental parameters for optimum composting: part 3 The effect of pH, nutrients, storage and paper content relative to composting. *Compost Science* 14(3):16-22.

JIMENEZ,E.I.; GARCIA,V.P.. (1989). Evaluation of city refuse compost maturity: A review. *Biological Wastes* 27:115-142.

JUNIPER,B.E.. (1990). The leaf from the inside and the outside: A microbe's perspective. *Microbial ecology of leaves.* Edited by Andrews,J.H. and Hirano,S.S.: Springer-Verlag.

KALBERMATTEN,J.M.; JULIUS,D.S.; GUNNERSON,C.G.; MARA,D.D.. (1982). *Appropriate sanitation alternatives: a planning and design manual.* The John Hopkins University Press. U.S.A.: World Bank Volume 2 of series.

KING,F.H.. (1939). *Farmers of forty centuaries or permanent agriculture in China, Korea, and Japan.* Jonathan Cape.

LEICH,H,H.. (1981). Norwegians test 21 composting toilets. *Biocycle* 22(2):22-23.

LENTNER,C.. (1981). *Geigy scientific tables; Vol 1- Units of measurement, body fluids, composition of the body, nutrition.* CIBA - Geigy Ltd.

LEONARD,R.E.; FAY,S.C.. (1978). *A compost bin for handling privy wastes: its fabrication and use.*. Forest Service Research note NE-254,U.S.D.A..

LEONARD,R.E.; PLUMLEY,H.J.. (1979). Human waste disposal in eastern backcountry. *Journal of Forestry* 77(6):349-352.

LODHA,B.C.. (1974). Decomposition of digested litter. In: *Biology of plant litter decomposition; volume 1*; edited by Dickinson,C.H.; Pugh,G.J.F.: Academic Press.

MACGREGOR,S.T.; MILLER,F.C.; PSARIANOS,K.M.; FINSTEIN,M.S.. (1981). Composting process control based on interaction between microbial heat output and temperature. *Applied and Environmental Microbiology* 41(6):1321-1330.

MARTIN,D.L.; GERSHUNY,G.. (1992). *The Rodale book of composting: easy methods for every gardener.* Rodale Press, Emmaus, Pennsylvania.

McKINLEY,V.L.; VESTAL,J.R.; ERALP,A.E.. (1985a). Microbial activity in composting - Part 1. *Biocycle* 26(6):39-43.

McKINLEY,V.L.; VESTAL,J.R.; ERALP,A.E.. (1985b). Microbial activity in composting - Part 11. *Biocycle* 26(7):47-50.

MILLER,F.C.. (1989). Matrix water potential as an ecological determinant in compost, a substrate dense system. *Microbial Ecology* 18:59-71.

MILLNER,P.D.; POWERS,K.E.; ENKIRI,N.K.; BURGE,W.D.. (1987). Microbially mediated growth suppression and death of salmonella in composted sewage sludge. *Microbial Ecology* 14:255-265.

MOTE,C.R.; GRIFFIS,C.L.. (1979). A system for studying the composting process. *Agricultural Wastes* 1:191-203.

MOTE,C.R.; GRIFFIS,C.L.. (1982). Heat production by composting organic matter. *Agricultural Wastes* 4:65-73.

MOTHER EARTH NEWS. (1983). Alternatives to the five-gallon flush. *Mother Earth News* 80,172-174.

MOTHER EARTH NEWS. (1984). Mother's compost commode. *Mother Earth News* 85,104-106.

N.Z. COMMITTEE ON UTILIZATION OF ORGANIC WASTES - Sixth Report. (1972). *Guidelines for municipal composting*. Ministry Of Works, New Zealand..

NAKASAKI,K.; SASAKI,M.; SHODA,M.; KUBOTA,H.. (1985a). Effect of seeding during thermophilic composting of sewage sludge. *Applied and Environmental Microbiology* 49(3):724-726.

NAKASAKI,K.; SASAKI,M.; SHODA,M.; KUBOTA,H.. (1985b). Change in microbial numbers during thermophilic composting of sewage sludge with reference to CO_2 evolution rate. *Applied and Environmental Microbiology* 49(1):37-41.

NAKASAKI,K.; SASAKI,M.; SHODA,M.; KUBOTA,H.. (1985c). Characteristics of mesophilic bacteria isolated during thermophilic composting of sewage sludge. *Applied and Environmental Microbiology* 49(1):42-45.

NIMPUNO,K.. (1981). The Vietnam toilet system. *Biocycle* 22(5):48-49.

NOVAES,R.F.V.. (1986). Microbiology of anaerobic digestion. *Water Science Technology* 18(12):1-14.

OREMLAND,R.S.. (1988). Biogeochemistry of methanogenic bacteria. In: *Biology of anaerobic micro-organisms. edited by Zehnder,A.J.B.*

POINCELOT,R.P.. (1974). A scientific examination of the principles and practice of composting. *Compost Science* 15(3):24-31.

POLPRASERT,C.; WANGSUPHACHART,S.; MUTTAMARA,S.. (1980). Composting Nightsoil and water hyacinth in the tropics. *Compost Science/Land Utilisation* 21(2):25-27.

PRESSEL,F.; BIDLINGMAIER,W.. (1981). Analyzing the decay rate of compost. *Biocycle* 22(5):50-51.

REED,C.S.; MIDDLEBROOKS,E.J.; CRITES,R.W.. (1988). *Natural systems for waste management and treatment.* McGraw Hill.

REEVES,J.B.. (1959). Sanitary aspects of composted sewage sludge and sawdust. *Sewage and Industrial Wastes* 31(5): 557-564.

RIGGLE,D.. (1990). Composting toilets reach the 90s. *Biocycle* 31(8):68-71.

ROTHBAUM,H.P.; DYE,M.H.. (1964). Self-heating of damp wool- Part 3. Self-heating of damp wool under isothermal conditions. *New Zealand Journal of Science* 7:119-146.

SCHOLZE,R.J.. (1985). Innovation in remote site waste treatment. *Biocycle* 26(6):37-38.

SCHUCHARDT,F.. (1985). Ein verfahren zur kompostierung von schweine-flussigmist unter zusatz von stroh und perlit. *Landbauforschung Volkenrode*,35. Jahrgang(1985) 1:11-19.

SCHULZE,K.L.. (1962). Continuous thermophilic composting. *Applied Microbiology* 10:108-122.

SHUVAL,H.I.; GUNNERSON,C.G.; DEANNE,J.S.. (1981). *Appropriate technology for water supply and sanitation-Vol 10:Night-soil composting.* John Wiley and Sons :World Bank: Vol 10 of series.

SIKORA,L.J.; RAMIREZ,M.A.; TROESCHEL,T.A.. (1983). Laboratory composter for simulation studies. *Journal of Environmental Quality* 12(2):219-224.

SIKORA,L.J.; SOWERS,M.A.. (1985). Effect of temperature control on the composting process. *Journal of Environmental Quality* 14(3):434-439.

SMITH,E.D.; POON,C.P.; STRUSS,S.R.; BANDY,J.T.; SCHOLZE,R.J.. (1984). *Appropriate* *technology for treating wastewater at remote sites on army installations: Preliminary findings.* Champain, ILL; Construction Engineering Research Laboratory (Technical report: N-160).

SMITH,M.E.. (1981). *Evaluation of compost toilets.* United States Department of Agriculture, Equipment Development Centre, San Dimas, California.

STONER,C.H.. (1977). *Goodbye to the flush toilet: water-saving alternatives to cesspools, septic tanks, and sewers.* Rodale Press Emmaus,PA.

STOUT,J.D.. (1974). Protozoa. In: *Biology of plant litter decomposition; volume 2*; edited by Dickinson,C.H.; Pugh,G.J.F.: Academic Press.

SULER,D.J.; FINSTEIN,M.S.. (1977). Effect of temperature, aeration, and moisture on co_2 formation in bench-scale, continuously thermophilic composting of solid waste. *Applied and Environmental Microbiology* 33(2):345-350.

SZPADT,R.. (1990). On-site composting of vegetable and animal wastes. *Agricultural and food Processing Waste - Proceedings of the sixth International Symposium on Agricultural and Food Processing Wastes. December 17-18, 1990 - Illinois.*

THOSTRUP,P.. (1985). Heat recovery from composting solid manure. *Composting of Agricultural and Other Wastes: Proceedings of a seminar organised by the Commission of the European Communities, Directorate-General Science, Research and Development, Environment Research Programme, held at Brasenose College, Oxford, UK, 19-20 March 1984.* Edited by Gasser J.K.B.: Elsevier Applied Science.

TOLLNER,E.W.; VERMA,B.P.. (1987). Apparent thermal conductivity of organic potting mixes. *Transactions of the American Society of Agricultural Engineers* 30(2):509-513.

U.S.ENVIRONMENTAL PROTECTION AGENCY. (1980). *Design manual: Onsite wastewater treatment and disposal systems.* U.S.ENVIRONMENTAL PROTECTION AGENCY: EPA 625/1-80-012.

VAN DER RYN,S.. (1978). *The toilet papers.* Capra Press, Santa Barbara.

VEROUGSTRAETE,A.; NYNS,E.J.; NAVEAU,H.P.. (1985). Heat recovery from composting and comparison with energy from anaerobic digestion. *Composting of Agricultural and Other Wastes: Proceedings of a seminar organised by the Commission of the European Communities, Directorate-General Science, Research and Development, Environment Research Programme, held at Brasenose College, Oxford, UK, 19-20 March 1984.* Edited by Gasser J.K.B.: Elsevier Applied Science.

VIEL,M.; SAYAG,D.; PEYRE,A.; ANDRE,L.. (1987). Optimisation of in-vessel co-composting through heat recovery. *Biological Wastes* 20:167-185.

WILEY,B.B.; WESTERBERG,S.C.. (1969). Survival of human pathogens in composted sewage. *Applied Microbiology* 18(6):994-1001.

WILEY,J.S.. (1962). Pathogen survival in composting municipal wastes. *Journal of the Water Pollution Control Federation* 34.

WILEY,J.S.; ASCE,A.M.; PEARCE,G.W.. (1957). A preliminary study of high-rate composting. *Transactions of the American Society of Civil Engineers* 122:1009-1032.

YOUNG,B.. (1986). *A background report on Clivis Multrum composting toilets at Kosciusko National Park.* National Parks and Wildlife Service, New South Wales.

APPENDIX 1

A.1 REACTOR ENERGY BALANCE

The energy balance of a self heating, compost reactor is:

$$Q_{produced}=Q_{ventilation}+Q_{conduction}+Q_{storage} \tag{A.1}$$

A.1.1 VENTILATION LOSSES

Calculation of saturated vapour pressure, moisture content and enthalpy is possible if dry bulb temperature and humidity is known (see chapter 3). Knowing these values for both the input and output air and the air flow rate allow calculation of the Watts removed by ventilation:

$$Q_{ventilation} = \Delta h * flow$$

h	= enthalpy	(kJ/kg(dry air))
flow	= air flow rate	(kg/sec)

A.1.2 CONDUCTION LOSSES

Knowing the air temperature on the inside and outside, the surface area of the reactor and the U factor of the reactor insulation, allows calculation of conduction losses:

$$Q_{conduction} = UA\Delta t$$

U	= heat transfer coefficient	(W/m^2K)
A	= surface area of insulation	(m^2)
t	= temperature	(^0C)

After the first trial, when upwards of 1 litre of liquid was found in the bottom of the reactor, it was realised that the source of most of this water was from condensation on the wall of the reactor.

Vapour condensation on the walls moves 25 ± 5% of the heat from the composting pile to the walls. Thus the calibration, as carried out with the electrical resistor, may not be valid. This is because the value of the internal surface resistance would change with a proportion of the heat transfer from condensation. A more accurate calibration would have been possible if the sensor was embedded in the reactor wall, thereby eliminating the internal surface resistance. However the surface resistance is small compared to the resistance of 50mm of batts, therefore this source of error was disregarded.

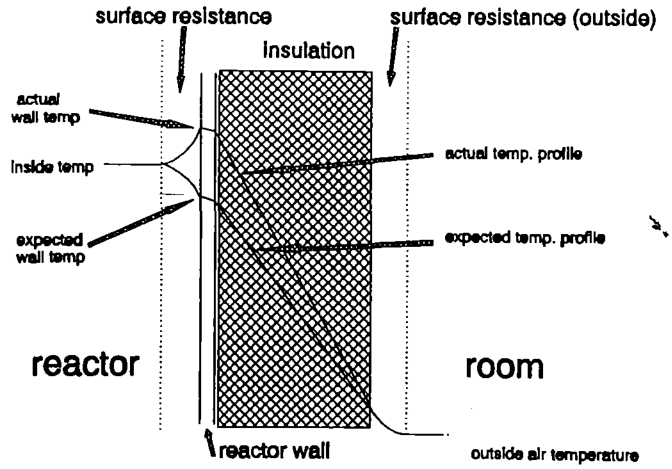


Figure A.1.1 Temperature profile through the wall of the compost reactor.

A.1.3 STORAGE CHANGES

Watts entering the storage can be calculated with a knowledge of the components' mass, specific heat, and the temperature change over a known time period:

$$Q_{storage} = \text{mass} * \text{specific heat} * \text{temp change} / \text{time}$$

The compost reactors had the following heat sinks:

	kg	specific heat
COMPOST a/ water(60%)	4.8	4190 J/kg.K
b/ organic(40%)	3.2	1000
PLASTIC REACTOR CASE	3.2	840
INSULATION	1.16 m^2	1147 J/m^2K

The temperatures used to calculate storage changes were:

COMPOST	- average compost temperature ([compost temperature t_p+reactor air t_m]/2)
PLASTIC REACTOR CASE	-air temperature of reactor (surface resistance effects eliminated as they will be the same for both measurements).

A.2 <u>ORGANIC MATTER OXIDATION</u> - Ash analysis

Volatile solids (organic material) can be burnt in a furnace at 550^{0}C, the remainder is ash. Ash will not be lost by biological oxidation and therefore the total quantity in the compost at the beginning of composting will be the same as at the end. With a decrease in the amount of organic matter as composting proceeds, the proportion of ash will increase.

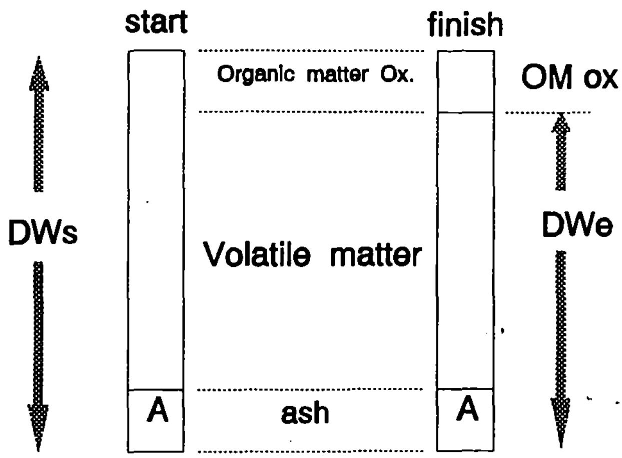


Figure A.2.1

At the start of composting:

$$A\%_s = \frac{A*100}{DW_s} \tag{A.2}$$

$$A = \frac{A\%_s * DW_s}{100} \tag{A.3}$$

Where: $A\%_s$ = % ash at start of composting

DW_s = dry weight at start (gms)

A = total ash (gms)

At the end of composting:

$$A\%_e = \frac{A*100}{DW_e} \tag{A.4}$$

$$DW_e = \frac{100*A}{A\%_e} \tag{A.5}$$

Where: $A\%_e$ = % ash at end of composting

DW_e = dry weight at end (gms)

By definition:

$$OM_{ox} = DW_s - DW_e \tag{A.6}$$

OM_{ox} = organic matter oxidised (gms)

Substituting equation A.5 in equation A.6:

$$OM_{ox} = DW_s - \frac{100*A}{A\%_e} \tag{A.7}$$

Use equation A.3 to calculate ash content (gms)

Then equation A.7 to calculate organic matter oxidised (gms)

Schulze's (1962) formula calculated the percentage reduction in volatile matter, and gave values 1 to 2 percentage points higher than this method.

A.3.1 <u>AMBIENT TEMPERATURE COMPOSTING</u> - Converting a vault toilet to a composting vault toilet.

A.3.2 INTRODUCTION

Vault toilets, with subsequent removal of all faeces and urine to a treatment facility, are being used increasingly within the DoC as a sewage containment mechanism. Vaults result in a high grade of environmental protection but can have high operating costs, especially if the vault contents are removed by helicopter. A large part of the waste is urine, so it follows that if urine is separated from faeces and disposed of by drainage or evaporation, a large reduction in the weight needed to be removed is achieved. The remaining faeces only require the addition of bulking material to compost successfully.

A.3.3 QUANTITIES PRODUCED

A comparison between the quantities produced from a storage vault and composting vault can be made:

	Storage Vault	Composting vault
Faeces (135 gms/person.day)	.135 litres	135 gms
Bulking material/person	nil	200 gms
Urine (1.2 L/person.day)	1.2 litres	nil (drained/evaporated)
Weight loss during storage	15% (evaporation) = 0.2 litres	30% (compost + water loss) = 100 gms
Net quantity per person.day	1.135 litres	.235 kg
Net weight for removal from 5000 users.	5.67 tonne	1.17 tonne

Table A.3.1 Comparison of the quantities to be removed from a storage vault with a composting vault.

The difference in design between a vault toilet and a composting vault toilet is small; one can be readily changed to the other.

Equation 4.14 shows that surface area, in conjunction with compost temperature, determines whether composting will succeed. It follows, that a low cost option for a compost toilet is a vault without insulation, but with sufficient surface area.

A.3.4 DESIGN

The additional elements needed to convert a storage vault to a composting vault are:

- addition of bulking material,
- separation of urine,
- porous floor with drainage collection.

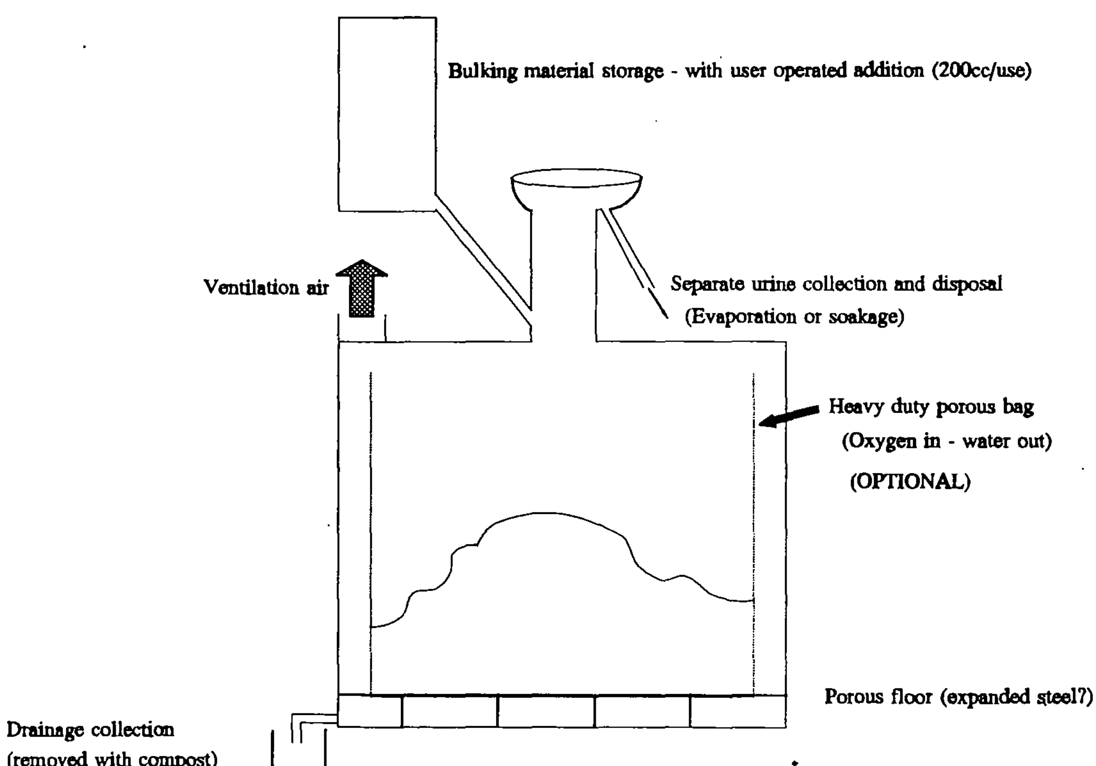


Figure A.3.1 The elements required for a successful composting vault toilet.

The sizing of the vault is important. Table A.3.2 and figure A.3.2 were derived from equation 4.14. For this design, temperature of the compost will be very close to ambient air temperature, therefore using the monthly average air temperature would produce a sufficient sized tank.

THE SURFACE AREA AND DIAMETER (if circular) OF A VAULT NEEDED FOR SUCCESSFUL COMPOSTING AT SPECIFIED TEMPERATURE AND USAGE LEVELS								
USERS/ DAY	10		15		20		25	
TEMP. °C	AREA cm^2	DIAM. m	AREA cm^2	DIAM. m	AREA cm^2	DIAM. m	AREA cm^2	DIAM .m
6	31813	2.01	47720	2.46	63627	2.85	79534	3.18
8	15462	1.40	23194	1.72	30925	1.98	38656	2.22
10	10070	1.13	15105	1.39	20140	1.60	25175	1.79
12	7390	0.97	11084	1.19	14779	1.37	18474	1.53
14	5789	0.86	8684	1.05	11578	1.21	14473	1.36
16	4727	0.78	7091	0.95	9454	1.10	11818	1.23
18	3972	0.71	5958	0.87	7945	1.01	9931	1.12
20	3409	0.66	5114	0.81	6818	0.93	8523	1.04
22	2973	0.62	4460	0.75	5947	0.87	7434	0.97
24	2627	0.58	3940	0.71	5254	0.82	6567	0.91
26	2345	0.55	3517	0.67	4690	0.77	5862	0.86

Table A.3.2 Surface area requirements for a composting vault toilet.

The necessary diameter can be seen graphically in figure A.3.2.

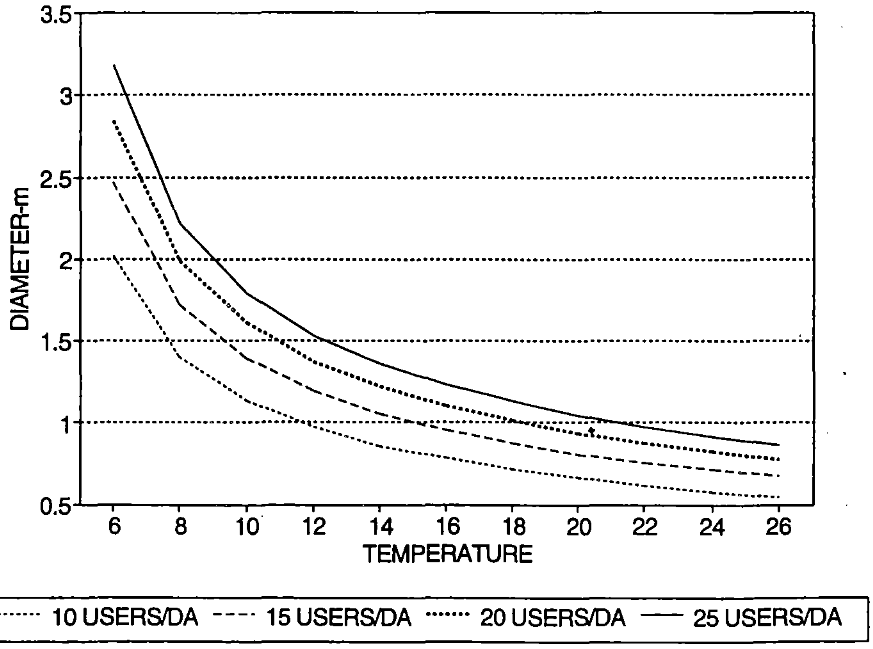


Figure A.3.2 The effect of temperature and usage rate on vault size (assuming a circular drum is used)

Such a toilet would provide a similar level of environmental protection to a storage vault (depending on mechanism for disposal of urine) but have less weight to be removed.

The porous bag liner is noted as optional. This will allow air to diffuse in from the side of the compost as well as from the top. The bag liner may have greater management considerations than composting considerations, in that the liner could be fitted with carrying straps and removed from the site without the need for shovelling compost from the vault..

Note: 1/ that this plan offers no suggestion as to the best means of emptying the vault. If the liner is used, then the top of the vault will almost certainly have to be removed; whereas if no liner is used an access door could be fitted to the side of the vault.

Note: 2/ the formula used to calculate surface area has not been verified; and the design has not been tested.